Individuelle Unterschiede in der Gesichterkognition im Kindes- und Jugendalter/
Individual Differences in Face Cognition across Childhood and Adolescence

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Zusammenfassung

Gesichterwahrnehmung und -gedächtnis (hier „Gesichterkognition“) sind wesentliche Facetten der sozialen Intelligenz. Eine harmonische Entwicklung dieser sozialen Fähigkeiten ist ausschlaggebend für die allgemeine Adaptation des Kindes an das Leben in einer heterogenen Umwelt sowie für seine erfolgreiche Sozialisation. Diese Relevanz macht die Gesichterkognition im Kindes- und Jugendalter zu einem zentralen Forschungsthema. Jedoch besteht eine Kontroverse über die Frage der frühen oder späten Reifung der Gesichterkognition während der Kindheit und Adoleszenz. Individuelle Unterschiede in der Gesichterkognition werden dabei meist ignoriert, wodurch die Fragestellung "frühe versus späte Reifung" möglicherweise verkürzt wird, denn in den unterschiedlichen Kohorten können sich mehr oder weniger starke individuelle Unterschiede zeigen. Außerdem machen es Lücken in der Untersuchung der individuellen Unterschiede unmöglich, die Assoziation der Gesichterkognition mit allgemeinen kognitiven Prozessen zu verfolgen, und auch die Spezifität der Gesichterkognition in der Kindheit und Adoleszenz bleibt offen.

In differenzialpsychologischen Arbeiten von Wilhelm et al. (2010) und Hildebrandt et al. (2011) wurde ein Ansatz für die Untersuchung der individuellen Unterschiede in der Gesichterkognition entwickelt. Basierend auf großen Stichproben von Erwachsenen wurde die Struktur der Gesichterkognition beschrieben und individuelle und altersbedingte Unterschiede untersucht. In Fortsetzung zu diesen Vorarbeiten sollte im Rahmen der aktuellen Dissertation dieser Ansatz für die Kindheit und Adoleszenz adaptiert werden. Im Rahmen der aktuellen Arbeit wurden folgende Fragen untersucht: a) Struktur der individuellen Unterschiede in der Gesichterkognition in der Kindheit und Adoleszenz und altersbedingte Unterschiede in dieser Struktur; b) Altersbedingte Leistungsunterschiede in der Gesichterkognition auf der Ebene latenter Faktoren; c) Spezifität der Gesichterkognition in der Kindheit und Adoleszenz.

Die Arbeit basiert auf einer querschnittlichen Entwicklungsstudie mit 338 (50% weiblich) Kindern, Jugendlichen und jungen Erwachsenen im Alter zwischen 6 und 21 Jahren, rekrutiert in Berliner Grundschulen, Gymnasien und Berufsschulen.

In drei Manuskripten wurde eine Reihe von Fragestellungen zur Gesichterkognition in Kindheit und Adoleszenz aufgegriffen. Hier formulieren wir ganz kurz die Hauptschluss-folgerungen.

Erstens, der Ansatz für die Untersuchung der individuellen Unterschiede ermöglichte das 2-faktorielle Modell der Gesichterkognition (Gesichterwahrnehmung (Faktor 1) und Gesichter-gedächtnis (Faktor 2)) zu replizieren und die Invarianz dieser Struktur über Kindheit und Adoleszenz zu demonstrieren. Zweitens, der Ansatz für die Untersuchung der individuellen

Unterschiede ermöglichte es, signifikante altersbedingte Leistungsunterschiede in der Gesichter-wahrnehmung und im Gesichtergedächtnis auf der Ebene der latenten Faktoren zu zeigen. Drittens, wir haben gezeigt, dass, obwohl das Niveau der Reifung der Gesichterkognition in hohem Maße mit der allgemeinen kognitiven Entwicklung verbunden ist, die Gesichterwahrnehmung und das Gesichtergedächtnis im Vergleich zur Objekterkennung spezifisch sind. Wir sind daher zu dem Schlussfolgerung gekommen, dass die Gesichterwahrnehmung und das Gesichtergedächtnis zum Teil spezifische Fähigkeiten sind, die einen besonderen sozialen Charakter haben. Die aktuelle Dissertation enthält eine Reihe von methodischen Empfehlungen, die einige offene Kontroversen betreffen, die mit der Messung der Gesichterkognition in der Kindheit und Adoleszenz verbunden sind (bezüglich Stimulus-Material, Design einiger Aufgaben). Der wichtigste methodische Beitrag der aktuellen Dissertation ist die Entwicklung der multivariaten Messung der Gesichterkognition in der Kindheit und Adoleszenz.

Abstract

Face perception and face memory („face cognition“) are basic facets of social intelligence. A harmonious maturation of these social abilities is crucial both for the adaptation of the child in a heterogeneous environment and for its successful socialization. This relevance makes the mechanisms of face cognition across childhood and adolescence a central topic for developmental science. Nevertheless, there is acute controversy over the issue of early or late maturation of face cognition during childhood and adolescence. In addition, individual differences in face cognition abilities were ignored so far, leading to the absence of information, how children in a given age cohort differ in these abilities and making it impossible to investigate the association of face cognition with general cognitive abilities; hence, the question about the specificity of face cognition in childhood and adolescence remains open.

Differential psychological work of Wilhelm et al. (2010) and Hildebrandt et al. (2011) developed an approach to the measurement of individual differences in face cognition. Based on the data of the large sample of adults a structure of face cognition was described and individual and age-related differences of face cognition abilities were investigated. In continuation of these studies, in the present dissertation, the individual differences approach was adapted for childhood and adolescence. In the present work we investigated: a) the structure of individual differences in face cognition in childhood and adolescence and age differences in this structure; b) age differences in face cognition abilities on the level of latent factors (abilities); c) the specificity of face cognition in childhood and adolescence.

The present dissertation is based on a cross-sectional developmental study with 338 (50% females) children, adolescents and young adults aged between 6 and 21 years, recruited in several primary schools, high schools, and vocational schools in Berlin, Germany.

In three manuscripts a series of research questions on face cognition in childhood and adolescence is addressed. The main conclusions are as follows:

First, the individual differences approach allowed to confirm the two-factorial model of face cognition abilities for accuracy tasks, including face perception and face memory and to demonstrate invariance of this structure across childhood and adolescence. Second, the individual differences approach allowed to demonstrate substantial age-related performance differences in face perception and face memory on the level of latent constructs. Third, we have shown that although the level of the maturation of face cognition abilities is highly related with general cognitive functioning, face perception and face memory are specific in comparison to object cognition. Thus, we conclude that face cognition abilities are partly specific abilities that have a special, social character. Moreover, the present dissertation contains a number of methodological recommendations concerning some of the open controversies related with the

measurement of face cognition in childhood and adolescence (regarding stimulus material, design of some tasks). The main methodological contribution of the current dissertation is the development of multivariate measurement of face cognition in childhood and adolescence.

Synopsis

1. Introduction

Faces are a rich source of social information. In the first period of an infant's life, the imitation of emotional expressions offers crucial experiences for social learning (Meltzoff, 2002). These experiences make communication by means of emotional expressions possible and foster the understanding of feelings and intentions of others (Fridlund, 1994). Faces also provide information about the focus of the attention of others, which is significant for social interactions (Tomasello, Carpenter, Call, Behne, & Moll, 2005). Furthermore, later in life facial recognition allows access to biographical information of social partners and their names, and triggers affective responses to familiar individuals (Breen, Caine, & Coltheart, 2000). The importance of face cognition was nicely summarized by my youngest participant (6 years): *"Es ist wichtig Gesichter zu sehen und wiederzuerkennen, um nicht allein zu sein"* [It is important to see and recognize faces, so you don't feel alone].

This relevance for everyday functioning makes the research on the mechanisms of face cognition across childhood and adolescence a central topic for developmental science. As it is widely known, already new-born infants already show a preference for face-like stimuli (e.g. Goren, Sarty, & Wu, 1975). In their „CONSPEC-CONLEARN Theory" Morton and Johnson (1991) postulate that babies are born with a predisposition to attend to faces and as a result they learn about them. Specifically, for the purpose of processing faces a subcortical system ("CONSPEC") directs babies to attend to faces or stimuli that have face-like first-order relations (specifically, moving patterns with three dark patches, representing the eyes and mouth ("configs" (Morton & Johnson, 1991)). As the child matures cortical systems take over, and from around four weeks of life the "CONLEARN" process causes the infant to start learning about individual faces (Hole & Bourne, 2010). This theory can be supported by reports about the predisposition to attend to faces by monkeys (see for review, Parr, 2011), and even by fetuses (e.g. Reid, Dunn, Young, Amu, Donovan, & Reissland, 2017).

Alternatively, Turati, Simion, Milani, and Umilta (2002), based on experimental findings (e.g., Simion, Valenza, Cassia, Turati, & Umilta, 2002), suggested that an early preference for faces is not related with congenital predispositions to attend to face stimuli. These authors found that faces are not specific stimuli, but prototypical top-heavy objects. That is, the immature visual system is more predisposed to perceive visual patterns with a focus in the upper visual field (top-heavy).

The domain-specific theory of Morton and Johnson (1991) and the domain-general theory of Turati and her colleagues (2002) lead to a similar conclusion: Preference for faces (or top-heavy objects) in an early period of life leads to increased experience with this stimulus type, and to the formation of facial expertise. Research on face cognition development is focused almost exclusively on the question of when, or at which age do children become face experts?

There are currently two alternative answers to this question. Late maturation is suggested by supporters of the specific development of face cognition; e.g. the maturation of holistic strategies (the ability to perceive a face as a whole) is closely linked to the proliferation of social experiences (Carey & Diamond, 1977; Carey, Diamond, & Woods, 1980; Diamond & Carey, 1977). Alternatively, supporters of general developmental theories suggest an early maturity of face cognition (see for review, McKone, Crookes, Jeffery, and Dilks, 2012). In addition, variance in face cognition abilities across individuals in early periods of life (in childhood and adolescence) has so far not been investigated. A closer look at the study of individual differences completes the research on the mechanisms of face cognition across childhood and adolescence at least in three directions. First, the individual differences approach completes the research on the age differences in face cognition abilities across childhood and adolescence, and thus, could be a solution of the controversy late versus early maturity of face cognition abilities. Second, from the research on individual differences in face cognition abilities follows in what way children in a given age cohort differ in face cognition abilities. Third, this approach allows to investigate, whether these differences can be explained in terms of differences in other abilities, such as general cognitive functions.

The lack of research on individual differences in face cognition in early periods of life goes along with several methodological concerns. Within the present dissertation we have analysed the main challenges of the actual research on face cognition abilities in childhood and adolescence (see paragraph 2) and we have tried to develop an alternative measurement approach, based on the investigation of individual differences in face cognition abilities in adulthood (see paragraph 3). Aims and expectations of the present dissertation are discussed at the end of the paragraph 3. The individual differences approach for investigation of face cognition abilities in childhood and adolescence in details is reported within three included manuscripts (see paragraph 4). Main findings are presented within paragraph 5. Future directions are discussed within paragraph 6. Main conclusions are presented within paragraph 7.

2. Methodological Challenges in Research on Face Cognition Abilities in Childhood and Adolescence

2.1. Debate about the Own-Age Bias: what Kind of Stimulus Material should be used?

One of the methodological challenges in investigating face cognition abilities in childhood is the choice of the stimulus material. On the one hand, there are reports supporting an own-age effect that is, inferior performance for faces of other age persons. Researchers, who demonstrate this effect, explain it with a lack in communication of children with adults and with the great importance of communication with peers for the development of such social skills as face cognition abilities. Therefore, children are better in recognizing faces of other children than older persons. Thus, supporters of this position recommend using children faces in experiments with children (Anastasi & Rhodes, 2005; Flin, 1985a; Hills & Lewis, 2011; Hills, 2012). More specifically, Hills (2012) reported that best results can be demonstrated for the recognition of peers. On the other hand, there are reports supporting a caregiver effect in favour of adult faces. Because imitating the behaviour of older persons is the most important instrument for learning in early periods of life, faces of adults and their emotional expressions are meaningful instruments for social learning in children (Bandura, 1962; Bandura & Walters, 1963; Meltzoff, 2002). Thus, it is expected that by using adult faces in experiments children should show better results (Chung, 1977; Picci & Scherf, 2016).

However, to our knowledge, there are no systematic studies of stimulus age effects using face-stimuli of different age from early childhood to early adulthood across a continuous age range of perceivers from early school age to early adulthood in a large sample applying multiple tasks.

2.2. Debate about the Measurement Instrument: which Paradigms should be used?

Another methodological problem in the investigation of face cognition abilities in childhood and adolescence is that prior evidence about age differences or longitudinal developmental changes was based on performance in single, rather than multiple tasks. In comparison to multiple measurement approach, using of single tasks does not allow to account for measurement error and the specificity of the measurement method (Wilhelm, Herzmann, Kunina, Danthiir, Schacht, & Sommer, 2010). This is a drawback, since results cannot be studied and interpreted in the context of abilities (on the level of latent constructs) and the findings cannot be generalized across different tasks that are conceivable assessment tools of face cognition abilities (Wilhelm et al., 2010). Furthermore, there is disagreement, what kind of paradigms for measuring face cognition abilities should be used (Burton, Schweinberger, Jenkins, & Kaufmann, 2015; Macchi-Cassia, Turati, & Schwarzer, 2011; Richler & Gauthier, 2014; Rossion, 2013). Using different paradigms and experimental designs lead to different conclusions.

2.3. Age Groups Comparison or Continuous Observations?

Generally, in developmental science, the quantitative moderator variable age has often been treated as a categorical variable and evidence about age differences is often based on the analysis of age groups. However, problems related to the categorization of continuous context variables are increasingly discussed (Hildebrandt, Lüdtke, Robitzsch, Sommer, & Wilhelm, 2016). MacCallum, Zhang, Preacher and Rucker (2002) warn about losing information about individual differences within groups and an increased risk of overlooking nonlinear relations. Information about individual differences within groups is lost because within groups, observations are treated as if they were equal regarding only group differences across the variables of interest. Hildebrandt, Wilhelm, and Robitzsch (2009) criticized the use of cutoff scores on a continuous moderator to build categories because those cutoffs are usually arbitrary. Therefore, continuous moderators should be treated as continuous variables, not as categorical variables; hence, age differences should be investigated based on age- continuous observations.

3. Individual Differences Approach for Measurement of Face Cognition Abilities: Main Principles

Above, we discussed the current state and main challenges for research on face cognition abilities in childhood and adolescence. We suggest that systematic measurement of individual differences using face-stimuli of different age from early childhood to early adulthood across a continuous age range of perceivers from early school age to early adulthood in a large sample and applying multiple tasks could be decisive in solving existing open questions and controversies. Below we discuss the main principles for measuring individual differences in face cognition abilities in childhood and adolescence.

3.1. Face Cognition is a System of Different Abilities

From different psychological traditions it follows that human cognition should be described as a hierarchically structured system of abilities. On the one hand, this view is presented within the psychometric tradition of Spearman's (1927) theory of general intelligence (g-factor), Horn and Cattell's (1966) theory of fluid and crystallized intelligence (Gf and Gc) and Carroll's (1993) three-stratum theory of cognitive abilities. Within the Russian psychological tradition, the most famous view on human cognition is Vigotsky's theory about higher cognitive functions as functional systems (see for review, Goldberg, Akhutina, Melikyan, Mikadze, Mervis, & Bisoglio, 2016). In the framework of this view, human cognition is understood as a structured system of interactive components (abilities) acting in flexible concert for the purpose of responding adaptively to changing conditions. An important communality of these theoretical positions for the present dissertation is the idea of mental processes as systems.

Nevertheless, the idea to consider mental processes as systems is widely developed only regarding general cognitive functioning, but much less with respect to social cognition. Similar to general cognitive functioning, social cognition can be viewed as consisting of numerous specific abilities that are necessary for complex social interactions (Allport, 1961; Guilford, 1950; Guilford, 1967; Thorndike, 1920). However, in contrast to general cognitive functioning, social abilities and skills have until now rarely been understood as systems, and their structural organization has rarely been investigated.

First steps in the investigation of social abilities as a system and their structural organization were realized within the research of face cognition (Herzmann, Danthiir, Wilhelm, Sommer, & Schacht, 2007; Herzmann, Danthiir, Schacht, Sommer, & Wilhelm, 2008; Wilhelm, Herzmann, Kunina, Danthiir, Schacht, & Sommer, 2010). Wilhelm and coworkers investigated the structure of face cognition abilities as a system of interpersonal abilities (Herzmann et al., 2007; Herzmann et al., 2008; Wilhelm et al., 2010). Following functional and neuroanatomical models of face cognition (Breen, Caine, & Coltheart, 2000; Bruce & Young, 1986; Burton, Bruce, & Hancock, 1999; Burton, Bruce, & Johnston, 1990; Ellis & Lewis, 2001; Gobbini & Haxby, 2007; Haxby, Hoffman, & Gobbini, 2000), Wilhelm and colleagues distinguished between face perception and face memory. Models of face recognition postulate an initial processing stage during which – upon seeing a face – pictorial information and invariant facial structures are extracted and maintained in the focus of attention for a short period of time. Neuroanatomically, these higher perceptual processes have been associated with the occipital gyrus and the lateral fusiform gyrus (Gobbini & Haxby, 2007). Invariant facial features are then encoded in long-term memory as representations that can later be activated when viewing a familiar face. In neuro-functional models these later face encoding and recognition processes are associated with the fusiform face area (Gobbini & Haxby, 2007; Kanwisher, McDermutt, & Chun, 1997). Recently, the dissociation between face perception and face memory was supported in a developmental study by Weigelt, Koldewyn, Dilks, Balas, McKone, and Kanwisher (2013). This study reported that face perception is adult-like already at five years of age and develops at the same rate as perception for other objects. Face memory, however, becomes adult-like around age ten and has a slower developmental trajectory than memory for other classes of objects. Thus, within this approach, face cognition is understood as an ability, which consists of numerous specific abilities, all of which are necessary for the adaptation in a heterogeneous environment and especially for a successful social life. This definition is important for the present dissertation.

3.2. Measurement Approach for Investigation of the Structure of Individual Differences in Face Cognition Abilities

From the definition of face cognition given above follows that the different facets of this ability should be taken into account when developing an instrument for assessing individual differences in face cognition. Thus, in investigating the structure of individual differences in face cognition abilities in adults, Wilhelm and colleagues (2010) used multiple tasks for measuring face perception and face recognition abilities, allowing to account for task specificity and measurement error.

Further, these multiple tasks included speed tasks and accuracy tasks. Performance in speed tasks is operationalized as time required for a correct response in a task with a low level of difficulty, where interindividual differences in performance speed are the focus of measurement. At the other side accuracy tasks are so difficult that a substantial proportion of the population would not solve all items or trials correctly, regardless of the time allowed for processing and to respond. Accuracy is defined as proportion of correct responses across all trials of a given task or task condition.

In all tasks participants were asked to show their maximal performance. In order to increase objectivity and to equate conditions for all participants no faces of famous persons were used. When familiar faces were employed, they were all based on initially unfamiliar faces learned under the same conditions.

3.3. Structure of Individual Differences in Face Cognition Abilities

Following the principles described above and based on the data of 151 participants, Wilhelm et al., 2010 were able to establish a measurement model of individual differences in face cognition abilities. The individual differences approach demonstrated that the structure of face cognition consists of the abilities of: 1) face perception accuracy, 2) face memory accuracy, and 3) speed of face cognition. Face perception accuracy is understood as the ability to discern the face as a whole, and to distinguish facial features and their configuration. Face memory accuracy is defined as the ability underlying the encoding, storing, and retrieving of faces from long-term memory. Finally, the speed of face cognition is the ability to perceive and recognize faces quickly. This model of individual differences in face cognition abilities clearly distinguishes between face perception accuracy and face memory accuracy, consistent with functional and neuroanatomical models of face cognition. The face cognition speed factor was only weakly related with the two accuracy factors that shared about half of their variance.

3.4. Specificity of Face Cognition Abilities

Furthermore, Wilhelm and colleagues (2010) tested, whether individual differences in face cognition abilities can be accounted for by other cognitive abilities such as perception and memory of non-face objects, mental speed, and general cognitive functioning. Based on the long-standing debate about the special status of face cognition in neuroimaging, clinical, experimental-psychological studies (e.g., Farah, Wilson, Drain, & Tanaka, 1998; Kanwisher, McDermott, & Chun, 1997; Maurer, Le Grand, Mondloch, 2002; Rossion, 2013; Tanaka & Gordon, 2011), the authors confirmed from a psychometric perspective that faces are not just another instance of object cognition, but are special. In the psychometric study of Wilhelm et al. (2010) the measurement model of individual differences in face cognition abilities (see above) was replicated in an independent sample of young adults (N = 209), which also provided evidence for the relative independence of the face cognition abilities from other cognitive abilities, such as immediate and delayed memory, mental speed, general cognitive abilities, and object cognition. These findings support the idea that face cognition abilities are special skills that can be considered as facets of social cognition.

3.5. Age Differences in Face Cognition Abilities

Expanding research on individual differences in face cognition abilities, Hildebrandt and colleagues investigated the relationship among face perception and face memory and among face cognition abilities and general cognitive abilities across the adult life span (Hildebrandt, Sommer, Wilhelm, & Herzmann, 2010; Hildebrandt, Wilhelm, Schmidek, Herzmann, & Sommer, 2011). This investigation addressed one of the most dominant theoretical concepts about life span changes of individual differences in cognition, the differentiation–dedifferentiation hypothesis (Balinsky, 1941; Garrett, 1938; Garrett, 1946).

According to the differentiation–dedifferentiation hypothesis, in early periods of life, cognitive abilities gradually differentiate from an amorphous general ability, up to a certain age, after which these distinct abilities are reintegrated or dedifferentiated. Later, a number of authors have reported methodological limitations of the early research on the differentiation–dedifferentiation hypothesis and suggested to re-test it with innovative analytical methods (Cunningham, 1981; Lindenberger & Baltes, 1997; Schaie, Willis, Jay, & Chipuer, 1989; Tucker-Drob & Salthouse, 2008; Tucker-Drob, 2009). These studies demonstrated the invariance of the structural configuration of cognitive abilities across the adult life span; hence, the validity of the differentiation–dedifferentiation hypothesis should be restricted.

Hildebrandt and colleagues tested the dedifferentiation hypothesis with the measurement model of individual differences in face cognition abilities and with a model testing specificity of face cognition above general cognitive abilities across the life span (Hildebrandt et al., 2010; Hildebrandt, et al., 2011). Based on reports about restrictions of the differentiation–dedifferentiation hypothesis, the authors expected stability of the structure of face cognition abilities and that these abilities maintain their distinctness from other cognitive abilities across the lifespan. Both expectations were confirmed: The authors showed invariance of the internal structure of face cognition from young adulthood up to very old age, and, furthermore, found no factorial dedifferentiation between face cognition abilities and general cognitive abilities.

Further, studies of Hildebrandt, Wilhelm, Herzmann, and Sommer (2013) and Liu, Hildebrandt, Recio, Sommer, Cai, and Wilhelm (2017) demonstrated that whereas accuracy of face perception and face memory are independent social skills, the speed of processing – including face cognition speed – is a more general ability and highly related with further speed abilities, covering different stimulus content areas.

3.6. Aims and Expectations of the Present Dissertation

The present dissertation aims to extend investigations of individual and age differences in face cognition abilities and to adapt the approach, developed in the studies reviewed above, to the early periods of life. More specific research questions are formulated in three manuscripts (part 4 of the present synopsis), here we briefly denote them.

Firstly, we wanted to represent face cognition in early periods of life as a system of interpersonal abilities (Herzmann et al., 2007; Herzmann et al., 2008; Wilhelm et al., 2010) (see Manuscript 1). On the one hand, our expectations following Wilhelm and colleagues (2010) were based on the distinction between face perception and face memory. However, we did not divide factors of accuracy and speed of face cognition abilities, based on the more current findings of Hildebrandt and colleagues (2013) and Liu and colleagues (2017) who found the specific status only for accuracies of these abilities. Thus, we expected to establish a two-factor model of individual differences in face cognition in childhood and adolescence.

Second, after establishing the measurement model of individual differences in face cognition in childhood and adolescence, we aimed to investigate age differences in this structure (see Manuscript 1). We extended the investigation of Hildebrand and colleagues (2010) (see above) and tested the differentiation hypothesis. Because of the lack of such research in the area of social abilities, our expectations based mainly on the investigations of the differentiation-dedifferentiation hypothesis in the area of general cognitive functioning (see for review, Tucker-Drob, 2009). Research on age differences within structural configuration of cognitive abilities with large samples of participants from different age ranges from early childhood and until late senescence demonstrate the invariance of the structural configuration of cognitive abilities across the whole life span and support restrictions of the differentiation-dedifferentiation hypothesis (e.g. Anstey, Hofer, & Luszcz, 2003; Bickley, Keith, & Wolfle, 1995; Hartmann, 2006; Juan-Espinosa, Garcia, Colom, & Abad, 2000; Juan-Espinosa, Garcia, Escorial, Rebollo, Colom, & Abad, 2002). Following these reports, we expected the invariance of the structure of face cognition abilities across childhood and adolescence.

Third, we investigated age differences in face cognition performance at the level of abilities (latent factors) (see Manuscript 1). As discussed above, the present dissertation is based on the approach which defines face cognition as a specific ability and aspect of social intelligence (Wilhelm et al., 2010). Following this definition of face cognition, we expected that specific neuroanatomical and functional mechanisms of this ability should have specific and prolonged development, which is also related with increasing experiences in communication. Thus, we expected that adult-like performance in face cognition can be observed only late, near adolescence. This expectation is consistent with the theory of specific development of face cognition (Carey & Diamond, 1977; Carey, Diamond, & Woods, 1980; Diamond & Carey, 1977).

Fourth, we assessed age differences in the structure and in performance of face cognition as a function of stimulus age (see Manuscript 1). This is the first systematic measurement of stimulus age effects across a continuous age range of perceivers from early school age to late adolescence in a large sample and using a multiple tasks approach.

Fifth, we investigated the specificity of face cognition abilities: whether these abilities are specific already in early school age or differentiate from other mental processes (object cognition, general cognitive functioning) until young adulthood (see Manuscript 2). Following the approach of Wilhelm and colleagues that face cognition is a specific ability and a basic facet of social intelligence and the theory of specific development of face cognition, we expected face cognition abilities to be specific already in the youngest age group studied (six-year olds). This expectation of no differentiation between face cognition and general cognitive abilities is also consistent with reports about limitations of the differentiation–dedifferentiation hypothesis. Further, we expected that specific face cognition maturation in performance cannot be completely explained by developmental improvements of object cognition and general cognitive functioning.

Sixth, we also elucidated individual differences in sub-processes of face perception such as holistic processing (the ability to discern the face as a whole) and the sensitivity to second-order relations (the ability to distinguish configurations of facial features). Avoiding the above discussed research limitations and using an individual differences approach, firstly, we addressed the question at which age these sub-processes of face perception are adult-like in general and how children differ across age. Second, we wanted to find predictors, which can explain this variance. For details see Manuscript 3.

4. Overview of the Included Manuscripts

Three manuscripts are included in the present dissertation. The first manuscript considers an alternative possibility for measurement of individual and age differences in face cognition abilities in childhood and adolescence based on an approach developed in studies of Herzmann et al. (2007), Herzmann et al. (2008), Hildebrandt et al. (2010), Hildebrandt et al. (2011), Wilhelm et al. (2010) (see above). This approach allowed the description of the structure of individual differences in face cognition abilities in early periods of life and to investigate age-related performance based not on the results in single tasks but at the level of abilities. Furthermore, we tested the modulation by the age of the stimulus pictures of age differences in the mean and covariance structure and in the performance of face cognition abilities. Continuing the investigation of the individual and age differences in face cognition abilities in childhood and adolescence, in the second manuscript we focused on the question about the specificity of face cognition abilities in early periods of life. Especially, we were interested in testing the hypothesis of differentiation face cognition abilities from other cognitive functions. We estimated age and individual differences in the covariance structure of face cognition abilities and other cognitive processes as well as variance in face cognition after accounting for interindividual variability in other cognitive processes.

The third manuscript completes the work with a more narrow topic – investigation of configural face perception. The manuscript reports the first study that used the multiple measurement approach for investigation individual and age differences in this process, based on data from a large sample and continuous observations across age.

All three manuscripts included in the present dissertation, are based on the data of 338 children, adolescents and young adults aged between 6 and 21 years (50% females), recruited in Berlin's primary schools, high schools, and vocational schools. The study received approval of the Ethics Committee of the Department of Psychology, Humboldt-Universität zu Berlin (Nr. 2013-44R) "Die Entwicklung der Gesichterkognition im Kindes- und Jugendalter" and by the Senate of the State of Berlin.

4.1. Manuscript 1: The Structure of Face Cognition across Childhood and Adolescence – A Basic Facet of Social Intelligence

1) Background: A successful development of face cognition abilities is crucial for the overall child development, as well as for children's adaptation to social life. Despite extensive research on face cognition development, the structure of individual differences in these abilities during childhood and adolescence has not yet been studied. The present study considers an investigation of age differences in the mean and covariance structure of face cognition abilities from childhood to young adulthood and their modulation by the age of the stimulus pictures. 2) Methods: 338 children, adolescents and young adults, aged between 6 and 21 completed two face perception and two face memory tasks. After establishing a measurement model of face cognition for the entire age range, age-differences in this structure were explored by Local Structural Equation Modelling (LSEM). 3) Findings of the present study are threefold: 1. They demonstrate an invariant two-factor structure of face cognition including face perception and face memory during childhood through early adulthood; 2. Results further show substantial improvements in performance across age, especially between 8 and 12 years old and after 14 years old; 3. Furthermore, we found no own-age bias on the structure as well as on the level of performance.

4.2. Manuscript 2: Face Cognition Abilities across Childhood and Adolescence are Strongly related with General Cognitive Functioning but become More Content-Specific

1) Background: Psychometric research on adults indicates that individual differences in face cognition abilities cannot be entirely explained through variance in general cognitive functioning and object cognition; hence, these abilities are specific. Face perception and face memory can be considered as crucial facets of social intelligence. However, it is still unclear, whether these abilities are domain-specific already in early periods of life or differentiate across

childhood and adolescence. In the present study we focused on this controversy from an individual differences perspective and tested the hypothesis of differentiation between face cognition abilities and other cognitive abilities. 2) Methods: The same sample of 338 participants, aged 6 to 21, as tested in Manuscript 1, completed tasks measuring face cognition abilities (face perception and face memory), object perception, object memory, fluid intelligence and working memory. After establishing a measurement model of face cognition and general cognitive functioning for the entire age range, age-differences in this structure were explored by Local Structural Equation Modelling (LSEM). 3) Results and Conclusions: Overall, our study supports about the notion of an early maturity of face cognition abilities. In our study already six-year old children demonstrated adult-like face perception and memory. Further investigation of individual differences in face cognition abilities in childhood and adolescence and their predictors suggest the following conclusion. The level of the maturation of face cognition abilities is highly related with general cognitive functioning but is also determined by experience during socialization. Thus, face cognition abilities are partly independent, specific abilities.

4.3. Manuscript 3: Configural Face Perception across Childhood and Adolescence

1) Background: Research on mechanisms of face perception in adults indicates that one of the important characteristics of face perception is its specificity and reliance on configural processing. However, there is still controversy about the age at which these properties reach adult-like levels in earlier periods of life. Individual differences in configural face perception have been largely ignored in research, causing a loss of information about variations across persons of the same age and making it difficult to study relationships with other abilities across age. 2) Methods: Within present study, we studied age effects and individual differences in distinct aspects of configural face perception in the same sample of 338 participants, as reported in Manuscripts 1 and 2. Participants completed a composite face task and spatially manipulated faces including face inversion. Further, analogous tasks with houses as stimuli were used to test

face-specificity. We also included tests of short-term and delayed face recognition abilities, working memory, and fluid intelligence, and studied covariates of individual differences in configural face perception and contrasted face perception with the perception of non-face objects (houses). We investigated individual differences in aspects of configural face perception by using generalized linear mixed effects modeling (GLMM). 3) The theoretical implications of our findings are at least threefold: 1. They support early maturity of configural face processing mechanisms (being already present in six years old children). 2. Results further suggest that theories on the development of face perception mechanisms need to refer to between-person variations because substantial individual differences in configural face processing emerge at all ages. 3. We provide novel evidence on the association between configural face processing and face memory abilities in childhood and adolescence. Furthermore, within present study we raised the question, whether the early age competence in configural face perception is face-specific (demonstrating composite and inversion effects also for houses).

The third manuscript was already published (please, see in References, Petrakova, Sommer, Junge, & Hildebrandt, 2018).

5. General Discussion

The present dissertation adresses the mechanisms of face cognition, social competencies that are relevant for everyday functioning. As mentioned in the introduction, faces provide a lot of information, such as age, gender, feelings and intentions of others, and focus of attention. Facial recognition allows access to biographical information of social partners and their names, and triggers affective responses to familiar individuals. For overall child development, as well as for children's adaptation to social life it is crucial to learn to correctly perceive, memorize and recognize faces and to understand the information that faces provide. In studies with adult persons it was already demonstrated that there are big differences between people in face cognition. Within the present study we focused on individual differences in face perception and face memory across childhood and adolescence.

5.1. Individual Differences Approach in Investigation of Mechanisms of Face Cognition Abilities in Childhood and Adolescence

As mentioned above, the main aim of the present dissertation was to extend investigations of Wilhelm and colleagues (2010) and Hildebrandt and colleagues (2010, 2011) about individual and age differences in face cognition abilities and to adapt their approach to early periods of life. Following this approach, we defined face cognition as a multidimensional set of interpersonal abilities. To measure different interpersonal abilities, which are included in face cognition (holistic face processing, perception of features of the face and configuration of them, ability to memorize faces, short-term recognition ability, long-term recognition ability), we developed an extensive task battery. Based on data of 338 children, adolescents, and young adults, aged between 6 and 21 years, we confirmed the two-factorial measurement model of face cognition for early periods of life, which includes the accuracies of face perception and memory. After establishing the measurement model, we investigated age differences in this structure and in performance at the level of abilities (latent factors). We concluded that although there is a significant increase with age in face cognition abilities in factor means, the modelling revealed measurement invariance for face perception and face memory and the relationship between these abilities.

Advantages of the individual differences approach are discussed in detail in Manuscript 1, here we briefly denote them: 1) First, results take into account measurement error and task-specific properties, and conclusions can be made on the level of abilities. 2) The investigation of the covariance structure and establishing its invariance is a crucial premise for objective comparisons of quantitative age differences for any given construct. 3) Within the present approach, age was used as continuous variable, which allows investigating age differences without loss of information about individual differences within each cohort, yielding a complete picture of age differences. Therefore, we derive our conclusions about the face cognition abilities in the early periods of life, based on the novel and objective measurement approach.

5.2. Specificity of Face Cognition Abilities in Childhood and Adolescence

Further, continuing the investigation of the individual and age differences in face cognition abilities in childhood and adolescence, we focused on the question about the specificity of face cognition abilities in early periods of life (see Manuscript 2). Following investigations of Wilhelm and colleagues (2010) and Hildebrandt and colleagues (2010, 2011), we estimated age and individual differences in the covariance structure of face cognition abilities and other cognitive processes as well as variance in face cognition after accounting for interindividual variability in other cognitive processes. General cognitive abilities were operationalized as working memory, fluid intelligence and object cognition (object perception and memory). We were able to demonstrate a strong association between face cognition abilities and general cognitive functioning with a tendency for dedifferentiation between these abilities. In contrast, face versus object cognition abilities became more distinct across childhood and adolescence. Our main theoretical implication is that the present results integrate the two conflicting views on the specificity of face cognition abilities in early life, discussed in the introduction (the theory of general cognitive development vs. the theory of face-specific development). The level of maturation of face cognition abilities is highly related with general cognitive functioning. However, it is important to note, that faces are partly specific social stimuli. Maturation of face cognition abilities is also determined by the factor as harmonious socialization of the child. This conclusion is important as extending previous investigations of individual and age differences of face cognition, providing evidence that already from early periods of the life face cognition abilities are partly independent, specific abilities.

5.3. No Own-Age Bias

The present dissertation is the first study providing evidence that is based on the systematic measurement of stimulus age effects across a continuous age range of perceivers from early school age to late adolescence in a large sample applying multivariate measurements.

In our data, there was no systematic effect of stimulus age on performance but invariance of the structure of face cognition abilities across stimulus age. Therefore, we contributed to the long-standing debate about the choice of the stimulus material in research on face cognition abilities in childhood and adolescence, which is important for future research: The faces of children and adults can be used equally. As discussed in Manuscript 1, during the whole period of growing up everything has a meaning: imitation of the behaviour of adults, interaction with peers (games, communication) and other experiences, making face cognition system flexible enough for successful recognition of faces of peers or persons, who are younger or older.

5.4. Individual Differences in Configural Face Perception are associated with Face Recognition Abilities.

Within the three manuscripts, included in this dissertation, we have closely concentrated on individual differences of sub-processes of face perception such as holistic processing (ability to discern the face as a whole) and the sensitivity to second-order relations (ability to distinguish configuration of facial features). Applying a multiple measurement approach, based on data from a large sample and continuous observations across age and using generalized linear mixed effects modelling (GLMM), we first provide strong evidence for significant variance in holistic processing and in sensitivity to second-order relations in childhood and adolescence. Including tests of short-term and delayed face recognition abilities, working memory, and fluid intelligence allowed to identify predictors, which can explain the variance in both sub-processes of face perception. Our findings suggest that immediate and delayed face recognition abilities predict better holistic processing, however, the higher sensitivity to second-order relations is associated only with delayed face memory. These findings are consistent with the results of investigations with adults (see the overview in the Manuscript 3) and complement them, indicating that already from early school age it is possible to observe a significant association between configural face perception and face recognition abilities.

5.5. Limitations or a Possible Solution for the Methodological Controversies?

As mentioned in the introduction, one of the problems for research on face cognition in childhood and adolescence is using single, rather than multiple tasks combined with disagreements about the kind of paradigms and experimental designs to be used. Manuscript 3 discussed in detail that different conclusions can follow from different tasks and even from different designs of tasks. Within this dissertation we attempted to avoid this problem by applying a multiple measurement approach. However, there are some limitations to our task battery, based on which recommendations for the future research can be formulated. First, for measuring holistic face processing we used a modified version of the composite task, developed by Richler and Gauthier (2014) and applied it to children and adolescence. However, further analysis of the structure of face perception and object perception reported in Manuscript 2, revealed a perfect correlation between composite tasks with faces and other objects (houses). This observation is consistent with the unexpected finding about the non-specificity of holistic face processing, reported in Manuscript 3. From these observations follows that the modified version or complete design of the composite task may not measure a specific holistic face processing ability. Further, using the simultaneous matching of spatially manipulated faces and houses tasks with upright and inverted presentations (Herzmann et al., 2008), we found significant interactions between spatial changes and inversion for face and non-face stimuli (see in more details in Manuscript 3). This may be due to the particular difficulty in change trials, which, as mentioned in Manuscript 3, underscores the need for establishing a unified procedure for measuring this sub-process of face perception.

6. Future Direction - Adaptation of the Individual Differences Approach for Investigation of Mechanisms of Face Cognition Abilities for the Practical Aims

As mentioned above, because of the advantages of our measurement approach we were able to thoroughly elucidate the full picture about individual and age differences in face cognition abilities within a healthy population of children, adolescents and young adults. Understanding the variance of such an important social skill within a healthy population is crucial for assessment, identification of deviations in social functioning.

The face cognition tasks used in this study can be applied to various fields where children of school age are to be tested. One area of special significance for research on the development of face cognition as a basic and central social competence is a continuation of this dissertation research including participants with different levels of social functioning (healthy participants with challenges in communication, introverts, persons with personality disorders (for example, schizoids), persons with Asperger syndrome, Autism Spectrum Disorders and other). Such research could make fundamental scientific contributions - understanding the variance in social skills within different groups of persons with difficulties in these abilities and identifying variables predict such individual differences. Understanding these processes might contribute to the development of training procedures.

7. Conclusions

For the first time in the literature, the present dissertation applied the individual differences approach to the investigation of face cognition abilities in childhood and adolescence. The individual differences approach allowed to confirm the two-factorial model of face cognition abilities for accuracy tasks, including face perception and face memory and to investigate age-related differences in these abilities on the level of latent constructs. Although the structure of face cognition abilities was found to remain invariant from childhood to early adulthood, age-related performance differences in these abilities were significant. The test of the effects of stimulus age on the invariance and performance in face cognition abilities across continuous age samples showed no own-age bias on the structure of face cognition as well as on the level of performance. Further investigation of individual differences in face cognition abilities in childhood and adolescence and their predictors suggest the following conclusions. The level of the maturation of face cognition abilities is highly related with general cognitive functioning. However, there was evidence for a specificity of face cognition in comparison to object cognition, which implies that faces belong to a specific type of stimuli that has a special, social character. Furthermore, it is the first study, which provides evidence of substantial individual differences in such sub-processes of face perception such as holistic processing and the sensitivity to second-order relations and their association with face recognition abilities. Moreover, the present dissertation allows a number of methodological recommendations concerning some of the open controversies related with the measurement of face cognition in childhood and adolescence (regarding stimulus material, design of some tasks). The main methodological contribution of the current dissertation is the development of multivariate measurement of face cognition in childhood and adolescence, that can be used in the future for scientific but also for practical aims.

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Original Research Manuscripts

Article

Manuscript 1: The structure of face cognition across childhood and adolescence – A basic facet of social intelligence

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Abstract: 1) Background: The abilities to perceive and remember faces is a crucial facet of social intelligence and their successful development is highly relevant for adaptation to social life. Despite extensive research on face cognition development, the structure of individual differences in this ability during childhood and adolescence is unclear. Here we investigated age differences in the mean and covariance structure of face cognition abilities from childhood to young adulthood and their modulation by the age of the stimulus pictures. 2) Methods: A sample of 338 participants, aged 6 to 21, completed four face perception and face memory tasks. After establishing a measurement model of face cognition for the entire age range, age-difference in this structure were explored by Local Structural Equation Modelling (LSEM). 3) Results: LSEM generally revealed measurement invariance for face perception, but a slight increase of factor loadings on face memory across age, occurring between 8 and 12 and after 16 years. The relationship between face perception and memory was however invariant from childhood to young adulthood (r = .75). Factor means showed a slight significant improvement of face perception and memory across participant age. Stimulus age neither influenced performance levels substantially, nor individual differences. 4) Conclusions: Despite substantial improvements in performance across age, the individual differences approach did not reveal early differentiation of the internal structure of face cognition but suggested a robust two-factor structure of face cognition during childhood through early adulthood that was not biased by own-age recognition effects. We derive conclusions for the multivariate measurement and conceptualization of face cognition abilities – a basic facet of social intelligence – across the early lifespan.

Keywords: face, perception, memory, cognition, age invariance, age differences, own-age bias, local structural equation modelling, childhood, adolescence

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1. Introduction

Faces are a rich source of social information; therefore, it is crucial for successful interpersonal interaction to correctly perceive, learn, understand, and recognize faces. From a developmental perspective, an age-norm-appropriate growth of face cognition abilities is at least as crucial as the development of established cognitive abilities. The relevance for everyday functioning makes the research on the mechanisms of face cognition across childhood and adolescence a central topic for developmental science focusing on cognitive abilities. However, the structure of face cognition across childhood and adolescence has so far not been investigated from a psychometric perspective.

In research on cognitive abilities a multivariate approach describing human abilities as a hierarchical or nested structure at the level of latent variables is well-established, which is also an indispensable approach to studying age differences in these abilities at the level of latent variables instead of observed scores in single face cognition tasks [69]. However, such an approach has rarely been applied to social abilities. As an exception, Wilhelm and colleagues proposed to consider face cognition abilities as substantial facets of social intelligence [34, 35, 72]. In their psychometric studies, these authors factorially differentiated face cognition in young adulthood into partly specific abilities of face perception and face memory accuracy and the speed of face cognition. All these abilities were factorially separable from object cognition and general cognitive abilities. Studies of the face cognition structure within its nomological net across the adult age range, essentially found it to be invariant from young adulthood to senescence [36, 37, 38]. In the present article we focus on individual differences in face cognition abilities across childhood and adolescence at the psychometric level and the average performance captured by latent variables.

1.1 The Psychometric Structure of Face Cognition Abilities

Psychometric research on human cognition describes abilities as hierarchically structured [6, 69]. This view is present in Spearman's theory of general intelligence (g-factor), Horn and Cattell's theory of fluid and crystallized intelligence (Gf and Gc) and Carroll's three-stratum theory of cognitive abilities [13, 43, 64]. These classic theories consider general intelligence as overarching a broad range of cognitive abilities. Similarly, to general intelligence, social intelligence can be viewed as consisting of numerous specific behaviours that are necessary for complex social interactions [1, 30, 31, 67]. However, in contrast to general cognitive abilities, social abilities and skills and their structural organization are not well understood. Wilhelm and coworkers were the first to investigate the structure of face cognition abilities within the nomological net of established human abilities [34, 35, 72]. They followed several principles.

First, in line with functional and neuroanatomical models of face cognition [8, 9, 10, 32, 33], Wilhelm and colleagues distinguished between face perception and face memory. These models postulate an initial stage of face cognition during which pictorial information and invariant facial structures are extracted and maintained in the focus of attention for a short period of time. Neuroanatomically, these higher perceptual processes have been associated with the occipital gyrus and the lateral fusiform gyrus [32]. Invariant facial features are then encoded in long-term memory as representations that can later be activated when viewing a familiar face. In neuro-functional models these later face recognition processes are associated with the fusiform face area [32, 45]. More recently, the dissociation between face perception and face memory was also supported in a developmental study by Weigelt and colleagues [70]. The study reported that face perception is adult-like already at five years of age, and it develops at the same rate as perception for other objects. Face memory becomes adult-like around age ten and has a slower developmental trajectory than memory for other classes of objects.

Second, in their studies of individual differences in face cognition, Wilhelm and colleagues used multiple tasks for measuring face perception and face recognition abilities in order to account for task specificity and measurement error. Third, the applied task battery adhered to a basic principle of psychometric studies on cognitive abilities – the distinction between speed and accuracy tasks [13, 25]. Performance in speed tasks is operationalized as time required for a correct response in easy tasks, where accuracy is generally high and interindividual differences in performance are manifest in the reaction times. Performance in accuracy tasks is operationalized as number of correct responses in difficult tasks, where interindividual differences in performance accuracy are the focus of measurement. Accuracy tasks are so difficult that a substantial proportion of the population would not correctly solve all items or trials, regardless of the time allowed for processing and response.

Individual differences in face cognition accuracy clearly differentiate between perception and memory [72]. For speed tasks, this distinction was not supported by the data [38]. The face cognition speed factor was only weakly related with the two accuracy factors that shared about half of their variance. Thus, based on confirmatory factor analyses, Wilhelm and coworkers described the structure of face cognition abilities as a three-factorial model [36, 38, 72]. Within this model, face perception (as a first factor) depicts the ability to discern the face as a whole, and to distinguish facial features and their configuration; face memory (factor 2) is the ability underlying the encoding, storing, and retrieval of faces from long-term memory; and the speed of face cognition (factor 3) is the ability to perceive and recognize faces quickly. Furthermore, the authors have shown that only half of the variance in face cognition abilities can be predicted by general cognitive abilities, including reasoning, working memory, object perception, immediate and delayed memory for objects. These findings by Wilhelm and coworkers support the idea that face cognition abilities are social skills that are distinct from general cognition.

1.2 The Psychometrics of Face Cognition across the Life Span

The relationship among cognitive abilities during the life span is not always constant [17, 64, 65]. The most popular theoretical concept about life span changes of individual differences in cognition is the differentiation–dedifferentiation hypothesis [3, 28, 29]. According to this hypothesis, in early periods of life, cognitive abilities gradually differentiate from an amorphous general ability, up to a certain age, after which these distinct abilities are reintegrated or dedifferentiated [3, 28, 29, 69]. However, a number of later reports showed invariance of the structural configuration of cognitive abilities across the adult life span [16, 47, 61, 68, 69] and criticized earlier studies of the differentiation–dedifferentiation hypothesis for methodological limitations and suggested using more innovative analytical methods.

Within the research of life-span changes in the structure of social abilities, Hildebrandt et al. addressed this question with respect to face cognition abilities [36]. After establishing a measurement model of face cognition, the authors explored age-related changes of individual differences using Multiple Group Covariance Structure Models and Local Structural Equation Modelling [39]. The loadings and intercepts of all measures were age invariant, indicating an equivalent tri-factorial structure of face cognition for adults at least up to age 80. Factor means showed substantial decrements in performance with increasing age, most pronounced for the speed of face cognition, but age decrements were also salient for face perception and face memory. In addition, the studies above showed that, whereas accuracies of face perception and face memory are independent social skills, speed abilities – including face cognition speed – is a more general ability and highly related with general mental speed, covering different stimulus content areas [37, 38, 49].

Thus, for face cognition in accuracy tasks two factors were established that are largely face-specific and invariant across the adult life span. This structure of face cognition shows no dedifferentiation in old age. However, as yet the differentiation-dedifferentation hypothesis has not been investigated for the early life span. Thus, it is unknown, whether changes occur in the structure of face cognition from childhood to young adulthood.

1.3 Challenges of Investigating the Development of Face Cognition

As discussed above, the relevance of social skills for everyday functioning motivated developmental research into the mechanisms underlying these abilities during childhood and adolescence. Although it is widely accepted that already newborns are able to distinguish faces from non-face objects [42], previous studies on developmental trajectories of face perception and face memory arrived at inconsistent conclusions about whether face cognition matures early [15, 51] or late [11, 12, 18, 19, 52, 53].

One reason for these inconsistencies could be the kind of stimulus material used for investigating face cognition abilities in childhood, in particular the age of the depicted model in relation to the age of the observers. On the one hand, there are reports supporting an own-age effect that is, inferior accuracy in perception and recognition of faces of other age persons [2, 15, 24, 40, 41]. The own-age bias in children is explained with lack of experience with adults (observing and communication) leading to relatively better performance for faces of other children. On the other hand, there are also reports supporting a caregiver effect in favour of adult faces. Here it is assumed that until puberty, adults have special significance for children, providing a high level of practice for their faces [14, 57].

Furthermore, researchers mainly provided evidence about developmental changes based on performance in single, rather than multiple, tasks. Another drawback of previous research on face cognition in childhood and adolescence is the assembling of rather arbitrary age groups to be studied and ignoring individual differences within age cohorts. One solution is to follow the principles applied in the above-mentioned studies on adults to investigate face cognition in childhood and adolescence and its psychometric structure, using multiple assessment paradigms allowing the description of abilities at the level of latent factors.

1.4 Aims and hypotheses of the present study

With the present study we aim to extend available psychometric studies of individual differences in face cognition abilities in young and old adults to childhood and adolescence [36, 72]. Following the distinction between face perception and face memory within accuracy tasks and their status as specific social abilities, we expected to establish a similar two-factor model of individual differences in face cognition in childhood and adolescence.

After establishing the structure of face cognition abilities, based on data from a large age-heterogeneous sample (aged 6 to 21 years) and using a multivariate task battery, we aimed to investigate age differences in this structure and to test the differentiation-hypothesis for the internal structure of face cognition [3, 28, 29, 69]. To this aim we used Local Structural Equation Modelling [39]. As mentioned above, there is a lack of such research in the area of social abilities. Thus, our expectations based mainly on investigations of the differentiation-dedifferentiation hypothesis in the area of general cognitive functioning. We followed more recent reports about restrictions of the validity of the differentiation–dedifferentiation hypothesis and expected invariance of the structural configuration of face cognition abilities across childhood and adolescence [16, 47, 61, 68, 69].

We investigated age differences in face cognition performance at the level of abilities (latent factors). Assuming that face cognition abilities are aspects of social intelligence and have specific functional, neuroanatomical, psychometrical properties, we follow the theory of face-specific perceptual development [15]. In terms of this theory, we expected that performance in face cognition abilities becomes adult-like only late (near adolescence) due to the increasing experiences in communication during this age.

Finally, we investigated age differences in the structure of face cognition as a function of stimulus age. In order to test whether own-age bias occurs, we assessed whether factor loadings for trials depicting stimuli in the age range of the participants show a maximum. The further the age of the model deviates from the age of participant, the lower should be the factor loading. In addition, we investigated age differences in performance in face cognition abilities depending on stimulus age. To test the presence of own-age bias we analysed whether participants' performance was better in trials with own age faces.

2. Materials and Methods

2.1 Participants

Our sample included 338 children, adolescents, and young adults between 6 and 21 years (50% females). Participants were recruited in Berlin's primary schools, high schools, and vocational schools. The distribution of participants by age and gender is presented in Table 1. Participants were included into the analyses if they had complete data (all trials of all tasks). From 338 participants 10 dropped out and there were technical problems in 16 cases. Thus, the final sample included N = 302 participants.

Age group	6-7	8	9	10	11	12	13	14	15	16	17	18-21	Total
N_{total}	23	24	23	34	43	23	22	29	21	26	31	29	338
N_{boys}	8	11	8	26	21	13	5	13	12	18	15	11	162
N_{girls}	15	13	15	8	22	10	17	16	9	8	16	18	166

Table 1. Number of participants per age group and gender

2.2 Stimuli and Apparatus

Face stimuli were photographs taken by the authors under standardized conditions regarding luminance, distance, camera settings, and instructions for the photographed person. A total of 460 frontal view color portraits (213 females), with neutral expression, without glasses, salient make-up, moles, or other facial marks were obtained from girls and boys aged between 4 and 18 years. In all photographs, face-unspecific cues (hair, ears, and clothing) were excluded by fitting the face into a vertical ellipse of 300 by 200 pixels (7.6 * 5.1 cm), thus all photographs were in the same format. For all portraits we obtained ratings of distinctiveness based on the deviation scale described by Wickham and colleagues [71]. Ratings were made by 12 young adults (8 females). Next, we selected portraits for the memory tasks by picking up less distinct faces. In each task, 50 % of the portraits were of females. The tasks were programmed in PsychoPy v1.82.01 [56]. Tasks were established and administered on notebooks: Lenovo Thinkpad, Modell E330, with a 13.3 monitor inch and a display resolution of 1366*768.

2.3 Tasks

2.3.1 Composite faces task

The composite task was a modified version of the full design, developed for adult participants by Meinhardt-Injac and colleagues [54], adapted for children and adolescents. Two composite-faces were presented sequentially, where the second composite-face was always accompanied by a cue (cf. Fig. 1). The cue was a green arch with fingers on each side, presented at the top or the bottom of the second composite-face, indicating which half of the face was relevant for the item. Participants indicated whether the cued half of the face was the same or different as the corresponding half of the first composite-face. An equal number of congruent and incongruent trials were included. Figure 2 shows all conditions implemented in this task.

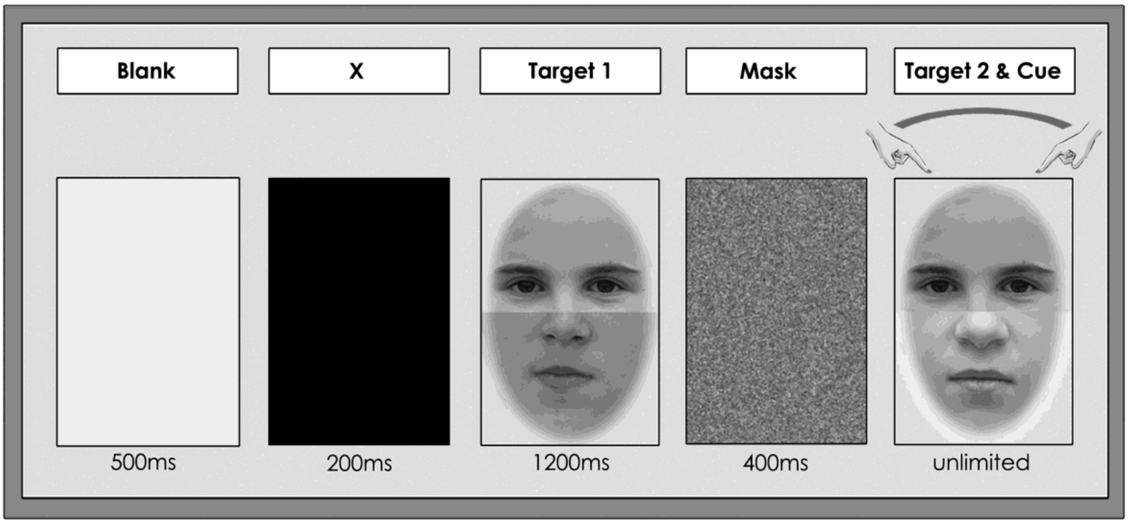

Figure 1. Trial sequence in Composite faces task.

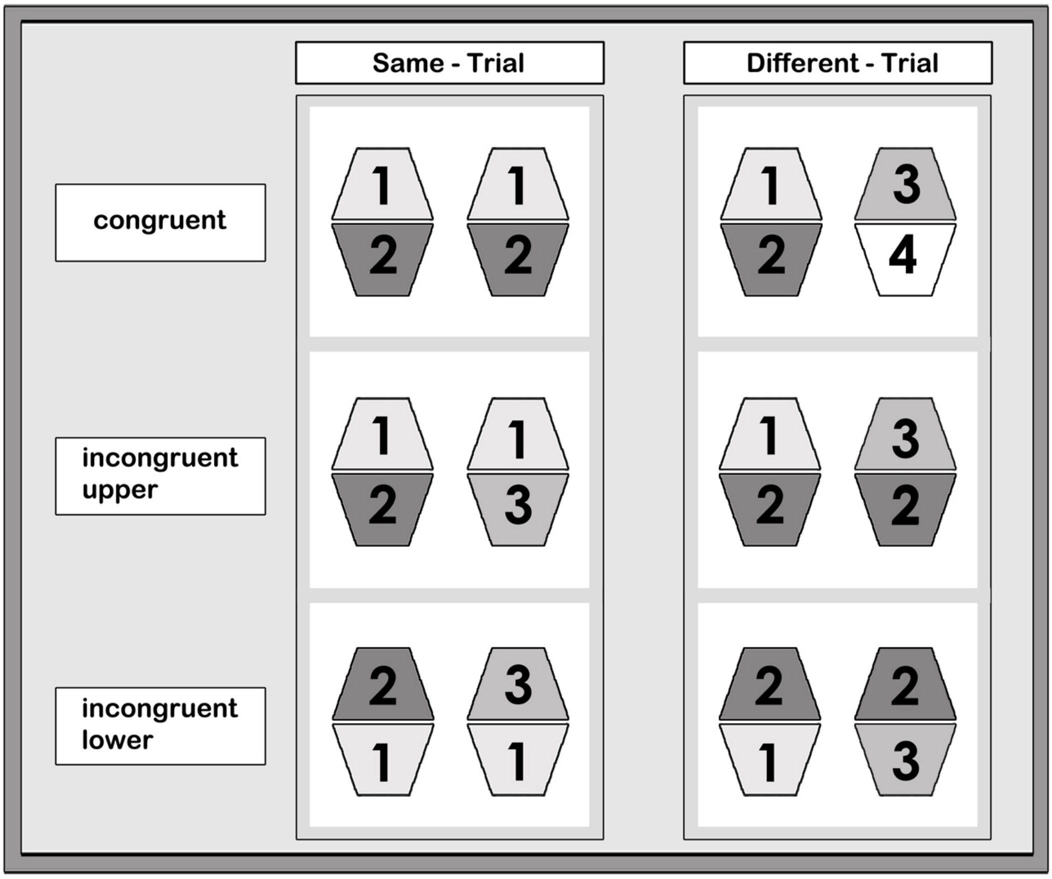

Figure 2. Overview of the conditions applied in the Composite faces task.

2.3.2 Simultaneous matching of spatially manipulated faces with upright and inverted conditions

This task was developed for adult participants [35, 36] and was slightly modified for the present study. Participants were to indicate whether two simultaneously presented faces were the same or different. Two faces were presented either upright (50% of trials) or upside down (inverted). The two faces were always derived from the same picture. Half of the trials presented the same face unaltered. In the other half of the trials a spatial relationship between features was altered in one of the faces. The spatial manipulations varied in extent, thereby manipulating difficulty, and were as follows: (1) moving the eyes up or down by 5 or 7 mm; (2) moving the eyes in- or outward by 5 or 7 mm; and (3) moving the mouth up or down by 3.5 or 5 mm — thus changing either the eyes–nose or the mouth–nose relation (Fig. 3 illustrates levels of difficulty). The value of the distance between the face features has been established on the basis of a pre-study with 100 participants. Example of a trial sequence is depicted in Figure 4.

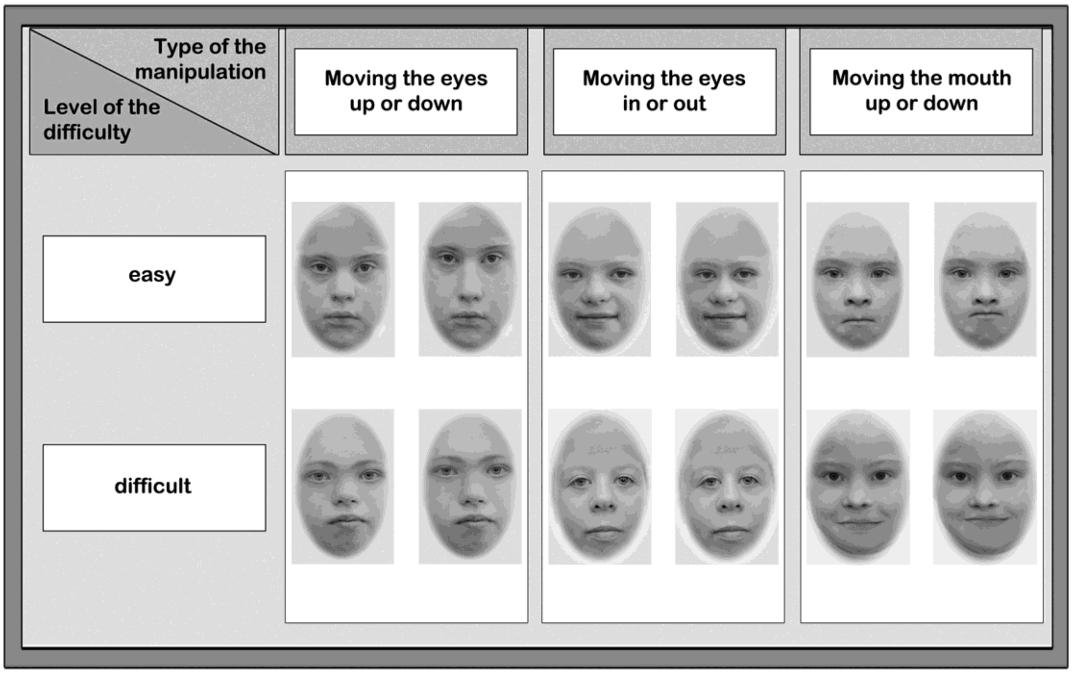

Figure 3. Overview of the difficulty levels applied in the Simultaneous matching of spatially manipulated faces with upright and inverted conditions.

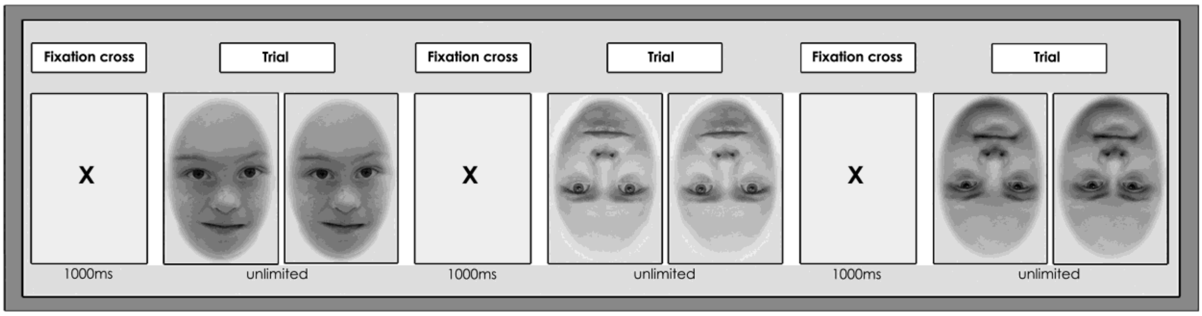

Figure 4. Trial sequence of the Simultaneous matching of spatially manipulated faces with upright and inverted conditions.

2.3.3 Learning and immediate memory of faces.

We administered the Acquisition curve task for measuring the progression of encoding and successful recognition of faces [35, 36]. The task includes three phases. In a study phase, participants memorize 15 faces, presented as a matrix for one minute. After the study phase an intermediate task followed expecting participants to decide whether two simultaneously presented series of letters, numbers, or symbols are the same or different. In the recognition phase each face learned during the study phase was shown twice, each time paired with a different, novel face. In every trial the learned face had to be indicated by a corresponding button press. This task includes four procedurally identical blocks of trials involving a total of 60 learned faces.

2.3.4 Delayed recognition of learned faces.

For measuring the delayed recognition of learned faces, we used the Decay rate task [35, 36]. Thus, at the end of the testing session participants were asked to indicate faces, which they had learned during the Acquisition curve task described above. Sixty learned faces appeared successively, by being paired with novel distractors. The learned face had to be indicated.

2.4 Scoring and data treatment

From each task, described above, we derived performance indicators for Structural Equation Modelling. There were four indicators for face perception: The indicators FP1 and FP2 represented the congruent and incongruent conditions, respectively, from the Composite faces task, and FP3 and FP4, represented the upright and inverted conditions, respectively, from Simultaneous matching of spatially manipulated faces. For face memory we derived five indicators: FM1, FM2, FM3, and FM4 represented four blocks of the Acquisition curve task and FM5 represented performance in the Decay rate task.

Further, each of the nine indicator described above, was determined for each of five stimulus age groups as correct responses across all trials of a given stimulus age, yielding a total of 45 indicators. The categorization into five groups was based on knowledge related to the morphological patterns of growth of the children's faces [7, 21, 22, 23, 63, 75]. The first group included faces of children from 4 to 6 years, which are still pretty similar to infant faces (round face with big eyes and plump cheeks). The second group included faces of children from 7 to 9 years, a group approaching adolescence (faces are more oval-shaped, plump cheeks are less pronounced etc.). We also included three groups of adolescents' faces according to three phases of maturity (10-12, 13-15 and 16-18 years). Figure 5 illustrates the assignment of trials to indicators according to tasks and stimulus age groups. There were no outliers in the univariate distributions of the indicators.

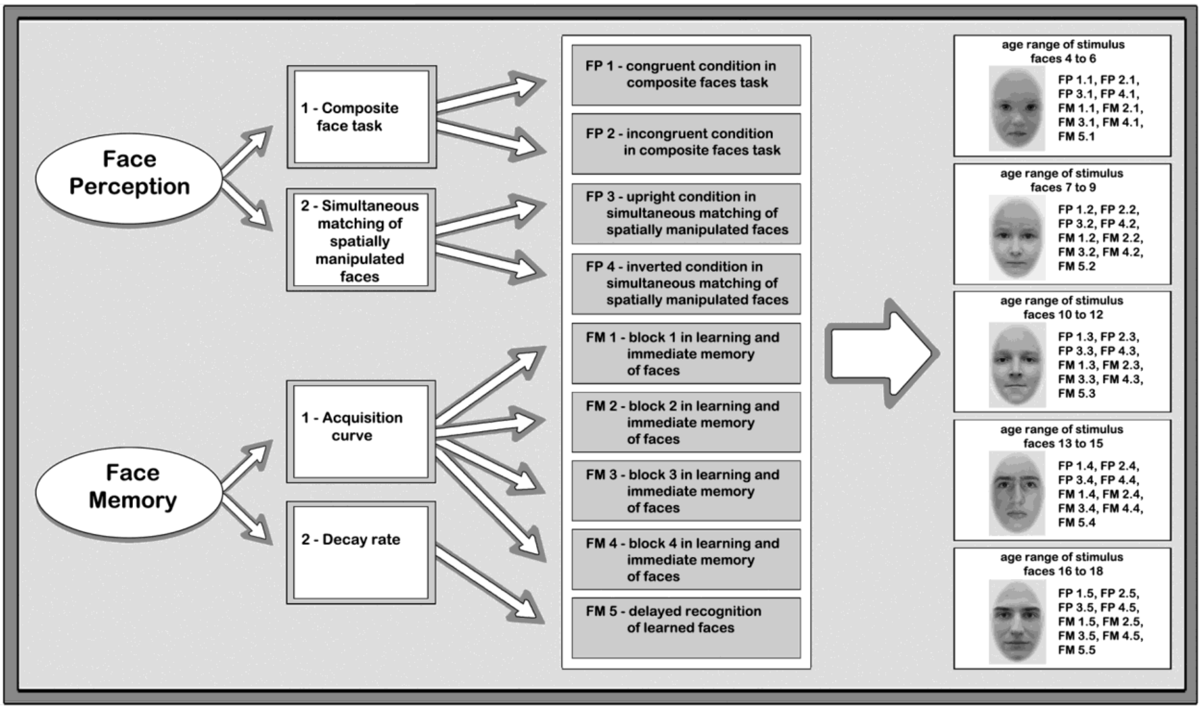

Figure 5. Schematic representation of the trial splitting depending on the stimulus age within each indicator provided by a given task. The splitting was used for the models investigating the invariance of face cognition abilities and age differences in performance depending on stimulus age.

2.5 Procedure

At the beginning of the testing session participants received a sticker with their identification number and started by completing the demographic questionnaire. Subsequently, they completed the computerized task battery, assessing face perception and memory. This session lasted about 1.5 hours, including breaks. There were always two proctors in the classroom. Depending on participants' age the instructions were more or less playful. Instructions were usually provided task-wise for the whole group. Younger children were visually instructed how to use their left and right index fingers for the two-choice reaction tasks and to keep their fingers on the response keys during the tasks. For older participants verbal instructions were sufficient.

2.6 Statistical analysis

Our first aim was to investigate the structure of individual differences in face cognition, including face perception and face memory during childhood and adolescence. To this aim, we used Structural Equation Modelling (SEM [46]) estimated by lavaan [60] in the R environment [58]. In SEM, multiple indicators (observed variables) are used to estimate a latent variable. Latent variables can be considered to represent traits controlled for measurement error and the specificity of measurement methods. Indicators assessing the same latent variable should correlate higher with each other than with indicators assessing a different latent variable. SEM further allows estimating the relationships between latent variables. Model fit is assessed by comparing the model-implied covariance matrix and the empirically observed covariance matrix between the indicators; model parameter are usually estimated by the Maximum Likelihood method in case of continuous variables. The fit of the matrices to each other is estimated through various statistical tests and fit indices, such as the $\chi 2$-test, the root-mean square error of approximation (RMSEA), and comparative fit index (CFI). Competing models are compared by evaluating the difference of their likelihoods by the $\chi 2$-difference test. Usually, CFI values above .95 are considered as excellent fit and CFI below .90 is considered unsatisfactory. RMSEA values above .08 and SRMR values above .05 are taken to indicate unacceptable fit.

To achieve our second aim of investigating structural age invariance, we used Local Structural Equation Modelling (LSEM [39]) implemented in the sirt package [59] of the R environment [58]. LSEM applies a kernel function for weighting observations around continuously defined focal values of a context variable, like age, and repeatedly fits SEMs along this moving weighting window [26, 27, 44]. Observations on each focal age – defined for the present study in steps of one year from 8 to 20 — receive a maximum weight. Sample weights fall off symmetrically with increasing distance of an observation from the focal value. Thus, we fitted the measurement model of face cognition with changing sample weights 13 times (from age 8 in steps of one year until age 20). SEM parameter functions across age are presented as results. To test parameter changes across age inferentially, we used a permutation test [39]. Using the test statistic based on permutations of age, the null hypothesis can be tested assuming that a given SEM parameter is constant across the values of age [39].

Our third aim was to examine age-related differences in face cognition abilities, also depending on stimulus age. In order to freely estimate latent means and variances, we scaled latent factors by the marker variable method [48], thus the loading and the intercept of a selected reference indicator for each construct was fixed to be one and zero, respectively. We then estimated a separate series of LSEMs for each group of stimulus age. As described above, there were five stimulus age groups resulting in five measurement model series estimated by LSEM across participants' age. Inferential tests were conducted in the same manner as described above for the overall models, not differentiating stimulus age. Finally, we used Growth Curve Modelling (LGCMs) to estimate performance level differences depending on stimulus age [50]. These models were estimated for single indicators one by one. LGCMs were conceptualized for modelling an initial value and a linear, quadratic, etc. change of a measured or latent variable across time. In the present study time is the age of the face stimuli used for a given task. Because there were five stimuli age groups, LGMCMs included five measured variables across which we estimated a linear and quadratic growth. LGMCM were then combined with LSEM to investigate whether linear and quadratic growth in perceiving and recognizing face stimuli of increasing age would change across participants' age. Figure 6 summarized all steps of the statistical analysis according to the research questions.

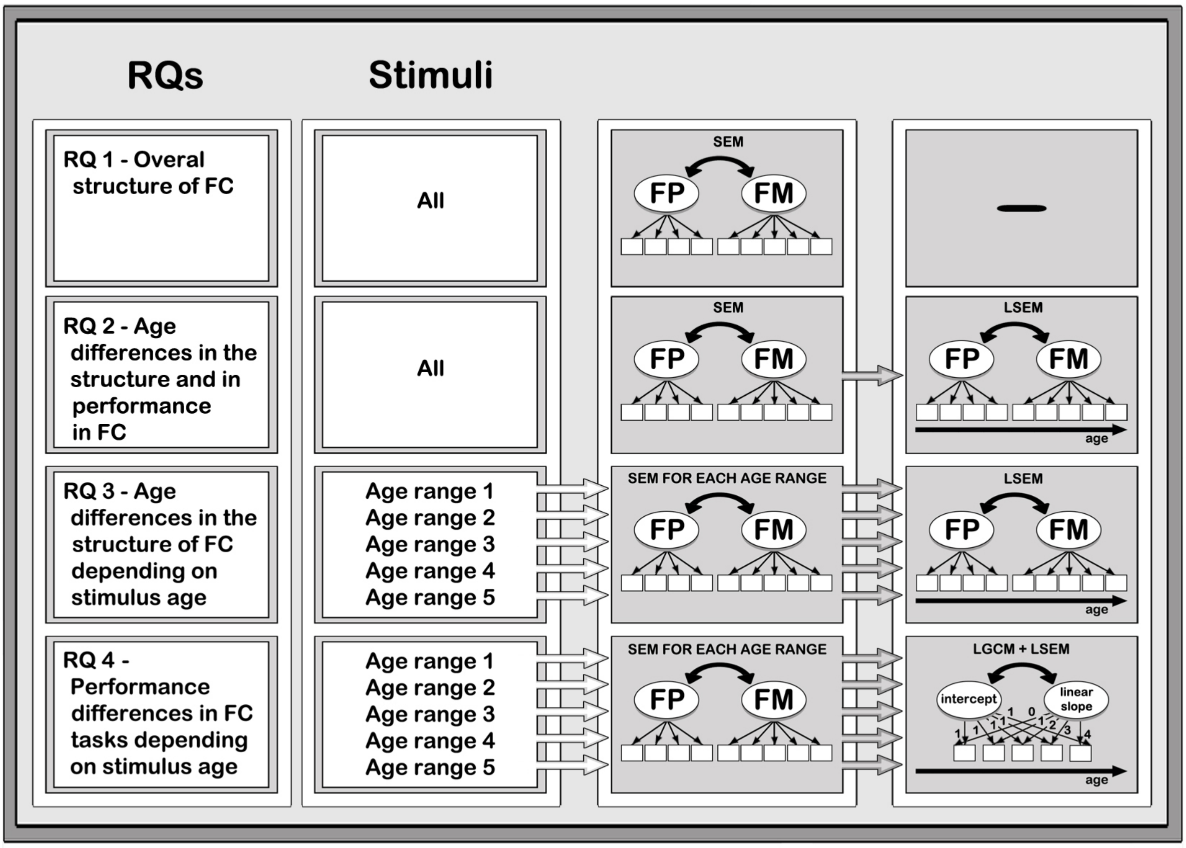

Figure 6. Summarizing overview of the sequence of applied statistical models.

3. Results

3.1. The Structure of Individual Differences in Face Cognition across Childhood and Adolescence

First, we estimated Model 1 (FC1; Fig. 7, Panel A) which assumed a single general face cognition factor to explain the shared variance of all nine performance indicators originating from face perception and face memory tasks. The fit of Model 1 was poor: $\chi 2$ (25) = 140.885, p = .000, CFI = .917, RMSEA = .124, SRMR = .073 (see Table 2). Factor loadings ranged between .55 and .77. Next, we estimated a second model, Model 2 (FC2; Fig. 7, Panel B), which assumed face cognition performance to be explained by two factors, face perception and face memory. The fit of Model 2 improved, $\chi 2$ (24) = 97.541, p = .000, CFI = .947, RMSEA = .101, SRMR = .060 (see Table 2). Factor loadings ranged between .61 and .79. The correlation between latent factor was reasonably different from 1 (FP/FM = .75). As summarized in Table 1, the Models FC1 and FC2 were compared with the Likelihood ratio difference test, showing that the less parsimonious Model FC2 is necessary for an adequate structural representation of individual differences in face cognition in childhood and adolescence.

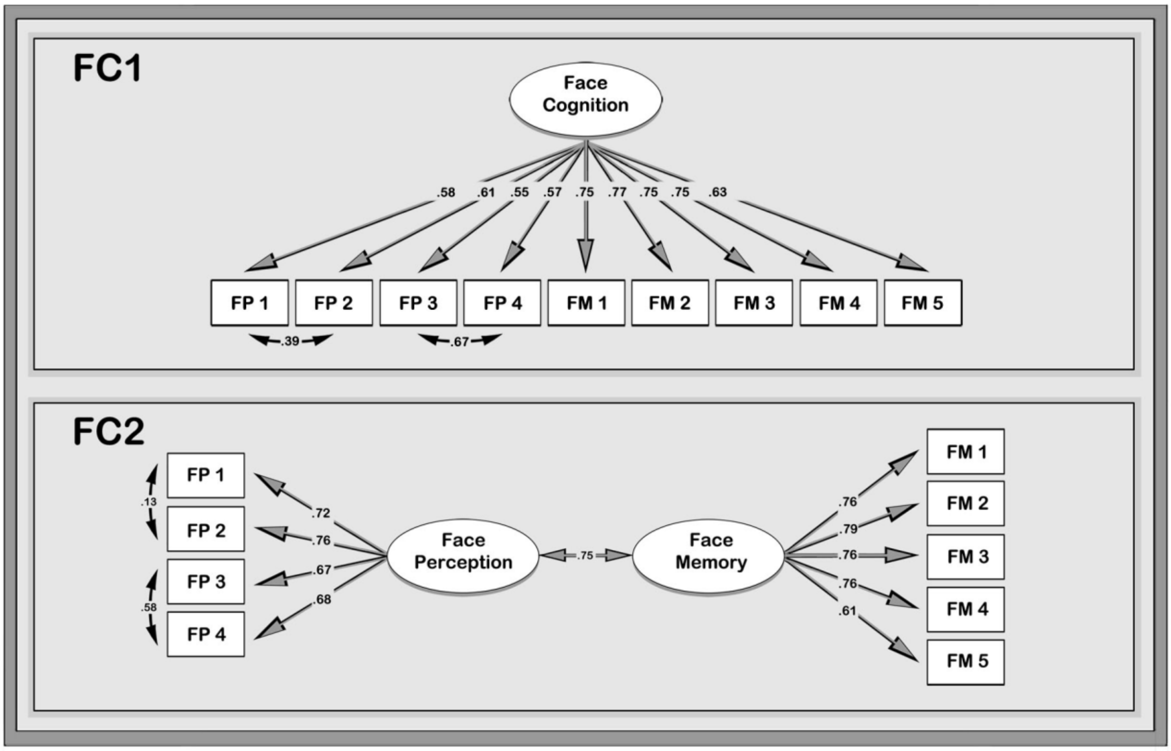

Fig. 7. Schematic representations of the Measurement Model of Face Cognition including one general factor (FC1, Panel A) and of the Measurement Model of Face Cognition including Face Perception and Face Memory (FC2, Panel B). FP1 = *composite faces task* – condition *congruent*; FP2 = *composite faces task* – condition *incongruent*; FP3 = *Simultaneous matching of spatially manipulated faces with upright and inverted conditions* – condition *upright*; FP4 = *Simultaneous matching of spatially manipulated faces with upright and inverted conditions* – condition *inverted*; FM1 = *Learning and immediate memory of faces* – first block; FM2 = *Learning and immediate memory of faces* – second block; FM3 = *Learning and immediate memory of faces* – third block; FM4 = *Learning and immediate memory of faces* – fourth block; FM5 = *Delayed recognition of learned faces*.

Table 2. Model fit and comparison of FC1 and FC2 models

Model	$\chi 2$	*Df*	CFI	RMSEA	SRMR	$\Delta\chi 2$ (Δdf)
FC1	140.885	25	.917	.124	.073	-
FC2	97.541	24	.947	.101	.060	43.344 *** (1)

Note: *** $p < .001$ – Alpha level was set to .01 in case of all statistical tests reported in this paper; CFI – Comparative Fit Index; RMSEA – Root Mean Square Error of Approximation; SRMR – Standardized Root Mean-square Residual.

3.2. Age invariance of the measurement structure

Next, we tested whether the parameter of the above described two-factorial model are invariant across childhood and adolescence. We used LSEM (see above) for this purpose.

As first objective within the LSEM approach, we inspected model fit indices with respect to their invariance across childhood and adolescence. Fig. 8 displays the test statistics of the RMSEA, CFI and SRMR indices of fit, estimated at focal values varying across age. Taking all three fit indices together we can conclude that the model fit was satisfactory and invariant at all focal age points.

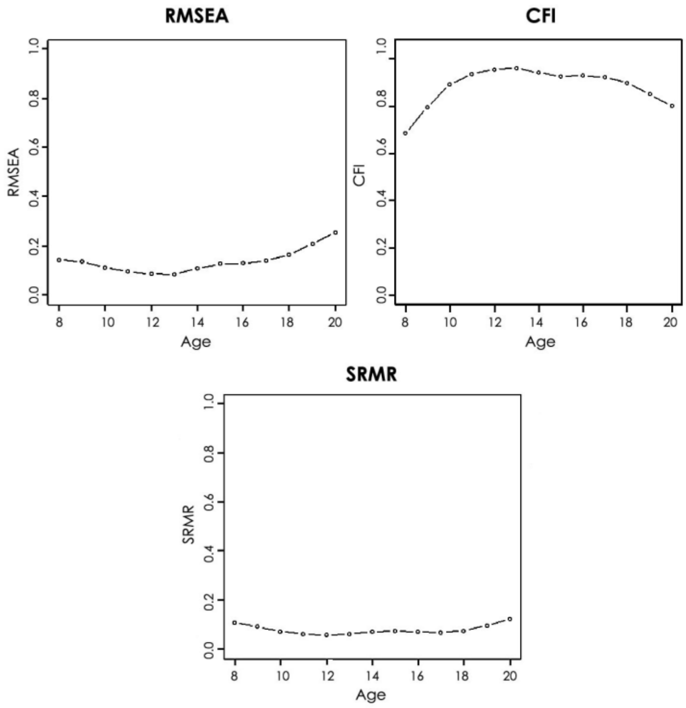

Fig. 8. LSEM estimated age gradient of loadings for fit indicies across age. CFI = comparative fit index; RMSEA = root mean square error of approximation; SRMR = standardized root mean square residual.

Estimated factor loadings along the age-weighted focal models are plotted in Fig. 9 and they demonstrate age stability of factor loading for most indicators of face perception, and a slight increase of factor loadings for face memory. The increase of loadings on face memory is mainly occurring between 8 and 12 years. LSEM further revealed a second slight boost of face memory loadings occurring after the age of 16 years. Fig. 9 additionally displays the relationship between face perception and face memory showing invariance across childhood and adolescence.

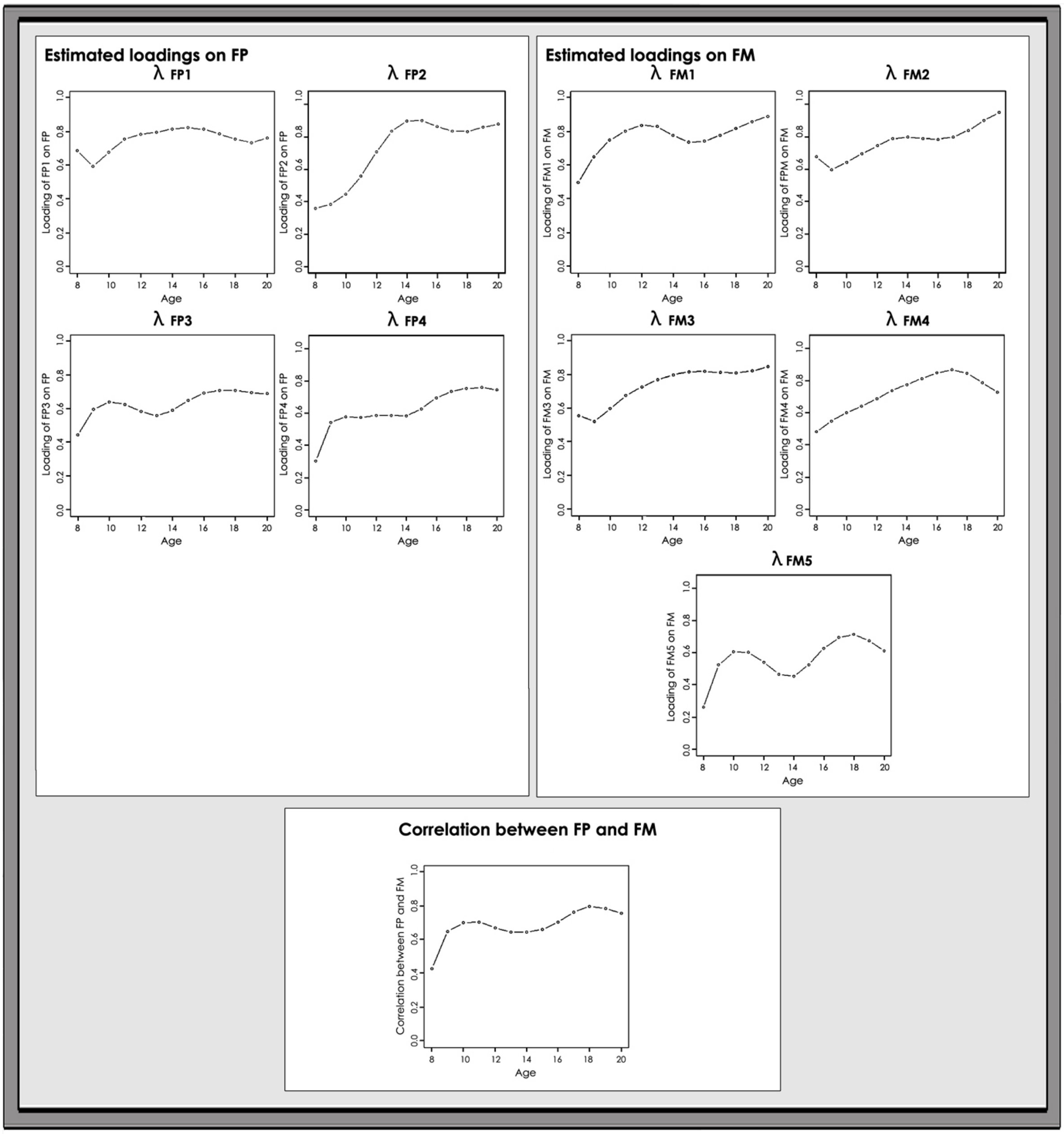

Fig. 9. LSEM estimated age gradient of loadings for face perception (left), face memory (right), and the correlation between face perception and face memory (below) across age.

Loading invariance on face perception, the consistency of the correlation between face perception and face memory, and the slight loading variations on face memory were inferentially confirmed by the pointwise test statistic based derived by the permutation test (see Fig. 10).

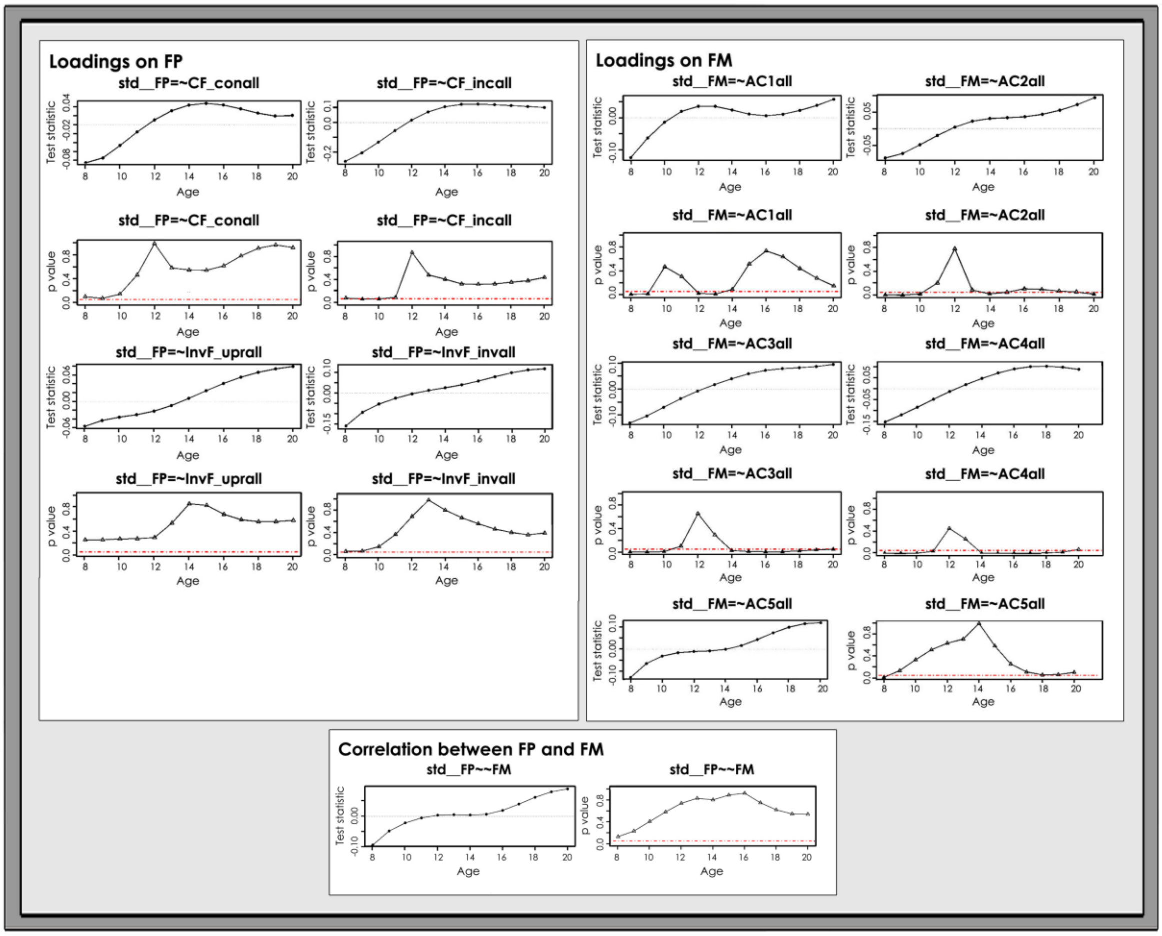

Fig. 10. Test statistics and pointwise *p*-values for inferentially testing parameter (loadings and factor correlation) variation across age. The figure shows the pointwise inferential tests conducted for loadings on the face perception (left) and face memory (right) factors, and the correlation between these two factors (below). The course of the test statistic across age is displayed in the upper and the course of corresponding *p*-values in the lower part of each figure. If a parameter at a certain focal point of age deviates from the average gradient, the *p*-value would appear below the boundary represented as a dotted red line in the figure. Additionally, the solid triangles are displayed for those pointwise tests which reveal statistically significant deviations. The deviation of the estimated factor loading on face memory from its weighted average functions is thus significant between the ages of 8 and 12 and above the age of 16.

3.3. Age differences on latent factor means across childhood and adolescence

Having established a measurement model of individual differences in face cognition which is mainly invariant across childhood and adolescence, we next explored performance differences across age on the level of latent factors. LSEM estimated latent factor means are plotted in Fig. 11. The trajectory of the estimated means along age in face perception followed an increase between 8 and 18 years and reached the peak in 18 years old. The trajectory of face memory revealed an increase between 8 and 14 years and reached the peak in 14 years old.

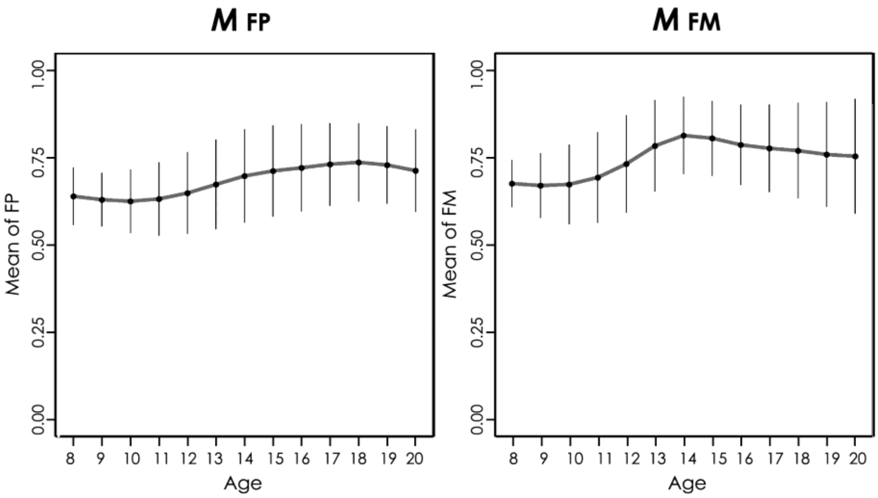

Fig. 11. Estimated latent factor means in face perception (left) and in face memory (right) age.

The results of the permutation test confirm this increase inferentially, starting with 8 years and continuing until 18 years in face perception and in face memory (see Fig. 12 for the permutation test based pointwise test statistic and corresponding p-values).

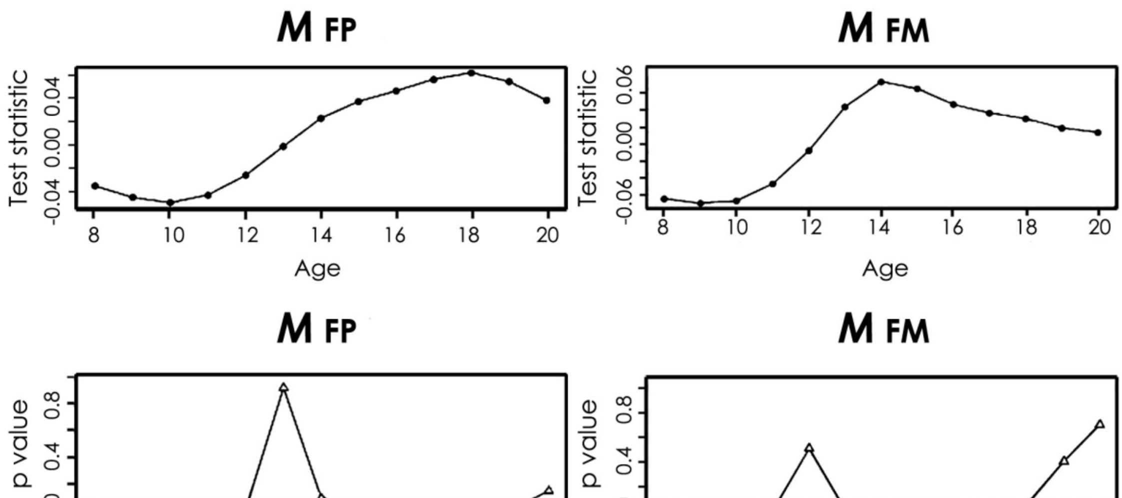

Fig. 12. Test statistics and pointwise p-values for inferentially testing variation in factor means across age. The figure shows the significance tests conducted for face perception and face memory performance at the latent level. The course of the test statistic across age is displayed in the upper and the course of corresponding p-values in the lower part of each figure. If the parameter at a certain focal point of age deviates from the average gradient, the p-value would appear below the boundary represented as a dotted red line in the figure. Additionally, the solid triangles are displayed for those pointwise tests which reveal statistically significant deviations. Thus, face perception and face memory performance are significantly deviating from their average functions between the ages of 8 and 12 and above the age of 14.

3.4. Age dependency of the measurement structure as a function of stimulus age?

Next, we investigated age invariance of the measurement structure depending on stimulus age. To this aim, we first established measurement models for each age specified group of stimuli, and thus, obtained five measurement models. The fit of these measurement models are displayed in Table 3.

Table 3. Fit of the face cognition measurement models for five groups of stimulus faces grouped by their age

Model	Age range of stimulus faces	$\chi 2$	Df	CFI	RMSEA	SRMR
FC2.1	4-6	42.052	25	.96	.048	.038
FC2.2	7-9	28.595	25	.99	.022	.031
FC2.3	10-12	33.162	25	.98	.033	.036
FC2.4	13-15	49.840	25	.94	.057	.044
FC2.5	16-18	65.431	25	.92	.073	.059

Note: FC2.1 – Final measurement model established in 3.1 and 3.2 estimated for faces of the age 4-6; FC2.2 – Final measurement model established in 3.1 and 3.2 estimated for faces of the age 7-9; FC2.3 – Final measurement model established in 3.1 and 3.2 estimated for faces of the age 10-12; FC2.4 – Final measurement model established in 3.1 and 3.2 estimated for faces of the age 13-15; FC2.5 – Final measurement model established in 3.1 and 3.2 estimated for faces of the age 16-18; CFI – Comparative Fit Index; RMSEA – Root Mean Square Error of Approximation; SRMR – Standardized Root Mean-square Residual.

Factor loadings in these measurement models ranged from .33 to .69. Factor correlation was comparable in all models with the correlation estimated on the bases of all stimuli. They varied from .63 (in the Model FC2.5) to .91 (in the Model FC2.2).

Having established five measured models for each group of stimuli, we applied LSEM for each of those models. In FC2.1 a slight increase of factor loadings on face perception and face memory occurred between 8 and 12 years and after 16 years. Correlations between face perception and face memory remained stable across age. FC2.2 shows the same tendency as FC2.1. In FC2.3 stability is observable for most of the indicators of face perception, and there is a slight increase of factor loadings on face memory across age, mainly occurring between 8 and 12 years and after 16 years. Also the correlation between face perception and face memory slightly increased across age. In FC2.4 there was again stability in the measurement precision of most indicators of face perception, and a slight increase of factor loadings on face memory across age. The correlation between face perception and face memory was invariant. And finally, in FC2.5 the same trajectory was observed like in FC2.4. In general, all five measurement models showed stability of the factorial structure of face cognition across stimulus age and the observed slight variation was strongly comparable with the models estimated for the aggregated stimuli, independently of their age.

3.5. Age differences in average face perception and memory performance depending on stimulus age

Last, to investigate age differences in performance as a function of stimulus age, we first estimated linear and quadratic growth curve models for each indicator separately. These models were intended to parameterize the growth above the initial value which may be due to the increasing age of the stimuli, because we assumed faces of older children to be generally better recognized. We obtained nine linear (assuming that performance linearly increases with increasing stimulus age, due to their individualization and distinctiveness) and nine quadratic models (assuming a further accelerated increase in more adult stimulus faces). The fit of these models are displayed in Table 4. Clearly, growth factors could not be identified for none of the indicators of face perception and face memory abilities (their variance was zero or nearly zero). Thus, we can conclude, that stimulus age has no effect on the average face perception and face memory performance.

Table 4. Fit of the linear and quadratic growth curve models investigating

Model	χ2	*Df*	*P*	*M* (lin. & quad.)	σ² (lin. & quad.)
Model FP 1a	5.343	10	.867	-.001	.000
Model FP 1b	3.793	6	.705	.000	.000
Model FP 2a	44.213	10	.000	-.002	.000
Model FP 2b	43.255	6	.000	.001	.000
Model FP 3a	25.575	10	.004	-.004	.000
Model FP 3b	19.402	6	.004	-.002	.000
Model FP 4a	9.922	10	.447	-.010	.000
Model FP 4b	5.612	6	.468	-.002	.000
Model FM 1a	80.990	10	.000	.019	.000
Model FM 1b	18.755	6	.005	.018	.000
Model FM 2a	51.469	10	.000	.008	-.001
Model FM 2b	11.366	6	.078	.016	-.001
Model FM 3a	113.815	10	.000	.014	-.001
Model FM 3b	20.848	6	.002	.031	.000
Model FM 4a	57.326	10	.000	.034	.000
Model FM 4b	13.345	6	.038	.019	-.001
Model FM 5a	89.757	10	.000	.009	.000
Model FM 5b	58.162	6	.000	.009	.000

Note: FP 1a – linear growth curve model for indicator FP1; FP 1b – linear and quadratic growth curve models for indicator FP1; FP 2a – linear growth curve model for indicator FP2; FP 2b - linear and quadratic growth curve models for indicator FP2; FP 3a – linear growth curve model for indicator FP3; FP 3b - linear and quadratic growth curve models for indicator FP3; FP 4a – linear growth curve model for indicator FP4; FP 4b - linear and quadratic growth curve models for indicator FP4; FM 1a – linear growth curve model for indicator FM1; FM 1b - linear and quadratic growth curve models for indicator FM1; FM 2a – linear growth curve model for indicator FM2; FM 2b - linear and quadratic growth curve models for indicator FM2; FM 3a – linear growth curve model for indicator FM3; FM 3b - linear and quadratic growth curve models for indicator FM3; FM 4a – linear growth curve model for indicator FM4; FM 4b - linear and quadratic growth curve models for indicator FM4; FM 5a – linear growth curve model for indicator FM5; FM 5b - linear and quadratic growth curve models for indicator FM5; M (lin. & quad.) – average linear and quadratic growth effects, depending on the model, linear effect is reported from the models only including linear growth, quadratic effect is reported from the models including linear and quadratic growth; σ² (lin. & quad.) – variance in the linear and quadratic growth effects

We were also interested to investigate whether participants' age would influence average recognition performance depending on stimulus age. Thus, we applied LSEM on the same growth curve models as described above to examine, whether the linear and quadratic growth factors would have variance at certain values of the participants' age. However, across all age-weighted models the variance of the linear and quadratic growth factors did not reach statistical significance.

In order to visualize the accuracy data across participant's age for all stimulus age groups we provide the Figures A1-A9 in the Appendix illustrate the difference in performance in all nine indicators in all age groups of participants depending on stimulus age. It is possible see that there was no own-age effect.

4. Discussion

This study complements the few hitherto available psychometric studies of individual differences in face cognition abilities across the lifespan and of age-related performance differences in latent face perception and face memory ability [35, 36, 72]. The present study focused on childhood and adolescence to systematically investigate – as customary in intelligence research – individual differences in a basic facet of social intelligence. We developed and evaluated tasks for measuring individual differences in face perception and face memory in childhood and adolescence by adapting an available battery for measuring these abilities in younger adults and tested 338 persons between 6 and 21 years. Based on these data we reported a number of novel findings. First, we could confirm the two-factorial model of face cognition accuracy for representing individual differences, including the accuracy of face perception and face memory. This factorial differentiation was observable for the entire age range of children and adolescents studied here. Second, we provided evidence for measurement invariance of face cognition accuracy throughout childhood and adolescence. Third, we showed substantial age-related performance differences in face cognition on the level of latent ability factors. And finally, we provided evidence that stimulus age does not influence the structure of face cognition abilities to a considerable degree. These main findings are discussed below.

4.1. A Model of Individual Differences in Face Cognition Abilities across Childhood and Adolescence

From our perspective, face cognition is a specific and multidimensional set of interpersonal abilities and can be considered a basic facet of social intelligence [34, 72]. As such an individual differences construct it requires an appropriate methodological approach for studying it within the context of other abilities. Wilhelm and colleagues [72] developed a broad variety of tasks stressing two important distinctions: The one between perception and memory of faces — based on functional and neurocognitive models of face processing and findings from developmental research [8, 9, 10, 32, 33, 69] — and the distinction between speed and accuracy performance, customary in individual differences research on cognitive abilities and the structure of intelligence [13, 25]. Wilhelm et al. established a three-factorial measurement model of face cognition, which included the accuracy of face perception and memory and the speed of face cognition [72]. Furthermore, they provided evidence that only about half of the interindividual variance in face cognition abilities in young adulthood can be explained by cognitive abilities such as object cognition, immediate and delayed memory, reasoning, mental speed, and working memory. That is, they are substantially specific abilities. To extend the studies of the individual differences in face cognition abilities to the adult lifespan, one broad study on age differences in face cognition was carried out a few years ago [36, 37, 38]. This study demonstrated invariance of the structure of face cognition abilities in adults until senescence. Furthermore, such authors as Hildebrandt, Liu reported the novel finding, that within the three-factorial measurement model of face cognition only two factors – accuracy of face perception and accuracy of face memory – are specific, and remain specific throughout the adult life span [37, 38, 49]. For the speed of face cognition abilities, however, no specificity was found. In the present study we adopted the approach as developed by Hildebrandt, Wilhelm [36, 37, 38, 72] to investigate individual differences in face cognition abilities in childhood and adolescence. Based on the test battery for the measurement of face cognition abilities, developed for adults [35, 36, 72, 73], we established tasks for measuring individual differences in accuracy of face perception and face memory using pictures of children and adolescents from 4 to 18 years and tested 338 children, adolescents and young adults aged between 6 and 21 years. Based on these data we modelled individual differences in face cognition abilities that were best described by two latent factors – face perception and face memory. Thus, the present study provides strong evidence that the tasks indeed measure the same construct distinctions as previous lifespan work, regardless of the difference in stimulus sets and other manipulations during adaptation to childhood age.

4.2. Age Invariance of the Structure of Face Cognition

As mentioned above, previous studies investigating face cognition abilities in childhood and adolescence, relied on single tasks, using different paradigms and experimental designs, arriving at different conclusions about the trajectory of age differences in face cognition abilities. The multivariate approach, used in the present study provides a number of advantages in the investigation of age differences in face cognition. First, this approach allows descriptions and conclusions on the level of latent constructs as opposed to the level of performance in specific single tasks; hence, the results take into account measurement error and task specific properties and permit a robust interpretation in terms of abilities. Second, the present approach allows the investigation of the covariance structure of face cognition abilities. Establishing invariance of a measurement model is a crucial premise for objective comparisons of quantitative age differences for any given construct. Third, we investigated age differences in the covariance structure of face cognition abilities using age as continuous variable as opposed to the more common – often arbitrary – construction of age groups. Using age as continuous variable instead of broad age groups allows investigating age differences without loss of information, yielding a complete picture about age differences, rather than fragments of it. By using these novel methodological advances in studying social cognition-related facets of interpersonal abilities, we tested and confirmed that the same abilities were measured across all age cohorts of participants from childhood to young adulthood. We could also show that test-specific artifacts do not notably bias the findings of quantitative age differences in face cognition constructs.

Thus, we can conclude that from early school age face cognition consists of two face-specific abilities, in other words, has an adult-like structure. Furthermore, the evaluation of the covariance structure from early childhood to late adolescence suggests invariance of face perception measurement, slight changes in face memory and stability of the relationship between these processes. Interestingly, we were able to show, that from early school age the relationship between face perception and face memory is of a very similar magnitude as reported for individual and age differences in face cognition abilities across adulthood (r = .75) [36, 72].

Thus, we observed no differentiation between face cognition abilities, suggesting that already 8 years old children demonstrate adult-like differentiation of the structure of face cognition abilities including face perception and face memory. This finding is consistent with more recent tests of the differentiation-dedifferentiation hypothesis within the investigation of general cognitive abilities, which suggest that the structure of these functions is invariant across the whole life span [16, 47, 61, 68, 69].

4.3. Age-Related Performance Differences in Face Cognition Abilities

The present study is the first to investigate early age differences of the covariance structure of face cognition abilities considering age as a continuous variable as opposed to the common arbitrary grouping into age groups. The age of the participants in the present study varied continuously between 6 and 21 years. Based on weighting observations to estimate the measurement model across age, we were able to show that face cognition abilities continuously improve across age from childhood to late adolescence. To our knowledge, this is the first study, where the onset and shape of age-related differences in face cognition abilities across childhood and adolescence was identified with such methodological scrutnity. Importantly, we report performance on the level of abilities as opposed to the usual way of investigating performance based on single tasks.

4.4. Own-Age Bias?

There was no systematic effect of stimulus age on performance and invariance of the structure of face cognition abilities. Following our main approach to investigate age invariance of the structure of face cognition, described in details above, we established separate models for each of the five age groups of stimulus faces. The two-factorial structure of face cognition was independent of stimulus age. Next, we tested, how age differences from childhood to late adolescence affect the measurement models depending on stimulus age and found invariance across participant age. Finally, we investigated the effect of stimulus age on average performance. We estimated linear and quadratic growth of performance with increasing stimulus age, assuming that faces of older children may be better perceived and recognized, because they show more uniqueness as compared with younger, still childish faces. We did not find any conclusive, robust and overarching growth of performance across increasing stimulus age and conclude that the stimulus material does not explain the variance in participants' face perception and memory performance.

The explanation of the present findings showing that young children recognize faces of peers and of children who are not much older similarly well like faces of adolescents and of young adults, may be based on the special meaning of adults for child development [57, 62]. In early periods of life, imitation is an important instrument for learning in general as well as for social learning [4, 5, 55]. The child imitates the behaviour of older persons (parents, older brothers and sisters or other older children, teachers etc.). Formation of attachment relationships with adults in early childhood likely shapes the computational goals of the visio-perceptual system, and the child does not have difficulties in the recognition of faces of older persons [62]. At the same time the child can recognize faces of peers also well. Spending time by interacting with peers (in games, kindergartens, schools etc.) increases experience with same age faces (peers), enhancing the ability to recognize these faces [62]. The explanation of the findings that older children (adolescents, young adults) recognize faces of peers similarly well like faces of younger children can also rely on the assumed role of experience in face cognition. In the meta-analysis of own-age bias studies Scherf and Scott discuss the *"Contact Hypothesis"* [62], suggesting that a lifetime of experience individuating faces from different age groups will mitigate the age bias. During the whole period of growing up the child acquires more and more different experiences, interacts with a large number of different people, and following, one may assume that it also shapes the computational goals of the vision-perceptual system, and the adolescent does not have difficulties in the recognition of faces of peers or persons, who are younger than her- or himself [62].

One explanation of the inconsistence of the present findings with reports from previous literature, supporting one of two most important positions within the research of face cognition in childhood (own-age bias vs. caregiver bias), can be seen in the novel methodological approach of the present study. The present study is the first to provide evidence that is based on the systematic measurement of stimulus age effects across a continuous age range of perceivers from early school age to late adolescence in a large sample. Furthermore, as mentioned above, in comparison to previous studies, we applied a multivariate measurement of face cognition abilities.

4.5. Novel Test Battery for Measuring Face Cognition Abilities in Childhood and Adolescence

Given the existence of valid performance measures, there is reason to hope that new constructs of interpersonal abilities can be used to predict real-life outcomes. Tests measuring interpersonal abilities — as the one developed along these lines of research – should therefore be applied in practical settings. If these new constructs are measured in age heterogeneous samples, it is important to provide evidence that the construct's measurement model is invariant across the age range, an issue rarely investigated in validation studies of test batteries for various abilities. Measurement invariance is an important prerequisite to ensure that the same construct is indeed measured in all participants of the application population. The face cognition tasks used in this study meet this requirement and can be applied in various fields where children of school age are to be tested. However, there is still opportunity to elaborate the test battery in future research by including further conceivable task paradigms.

One area of special significance for research on the development of face cognition as a basic and crucial social competence is the training of face perception and face memory in individuals who lack the rudimentary skills necessary for successful facial communication – for example, individuals with Autism Spectrum Disorder or Asperger's Syndrome. Autism is clinically diagnosed as impaired socialization and communicative abilities in the presence of restricted patterns of behaviour and interests [74]. Children with Autism Spectrum Disorder (ASD) frequently fail to respond differentially to faces over non-face objects, are impaired in their ability to recognize facial identity and expression, and are unable to interpret the social meaning of facial expressions [66]. To our knowledge, there is no special training evaluation, based on multivariate approach of training success based on a complete set of face cognition abilities [20].

5. Conclusions

We investigated, for the first time in the literature, changes in the covariance structure of face cognition abilities including face perception and face memory from childhood to early adulthood and reported age-related differences in these abilities on the level of latent constructs. Face cognition is a highly relevant facet of social cognition, and successful development of this ability space plays an important role for social, emotional, and cognitive development. Although the structure of face cognition abilities was found to remain rather stable from childhood to early adulthood, age-related performance differences in these abilities were substantial. Furthermore, this is the first study investigating the effects of stimulus age on the invariance and performance in face cognition across continuous age samples. We showed no own-age bias on the structure as well as on the level of performance. Finally, within our study we have established a novel test battery for measuring individual differences in face perception and face memory in school age, which in future can be used for scientific and practical aims.

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Author Contributions: "A.P., A.H., and W.S. conceived and designed the experiments; A.P. performed the experiments; A.P., A.H. and O.W. analysed the data; A.P., A.H., and W.S. wrote the paper. O.W. further edited the paper."

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Appendix

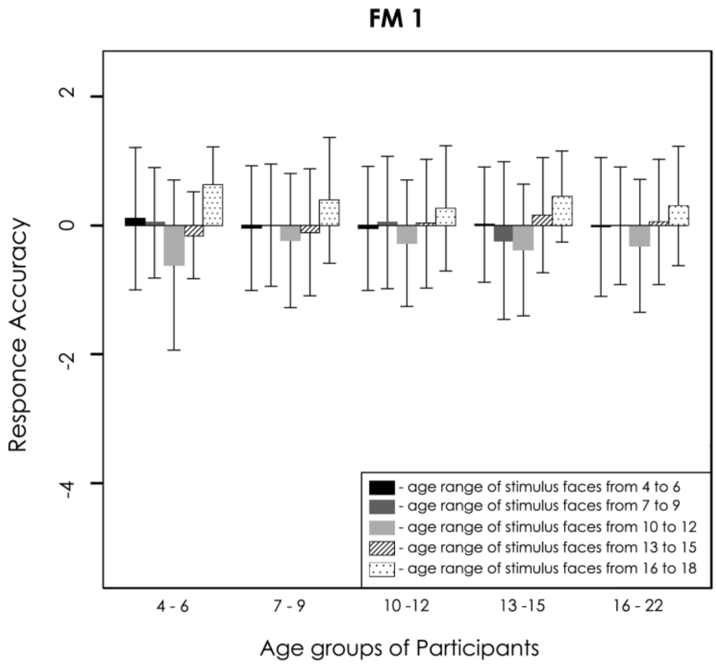

Figure A1. Average within group response accuracy across participant's age in the first block of the Acquisition curve task for different stimulus age categories. Response accuracy has been z-standardized within participant age groups.

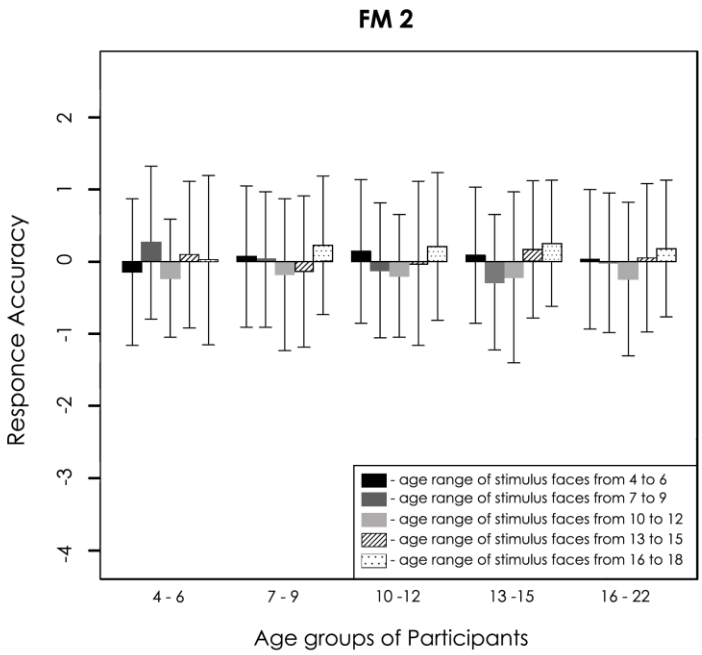

Figure A2. Average within group response accuracy across participant's age in the second block of the Acquisition curve task for different stimulus age categories. Response accuracy has been z-standardized within participant age groups.

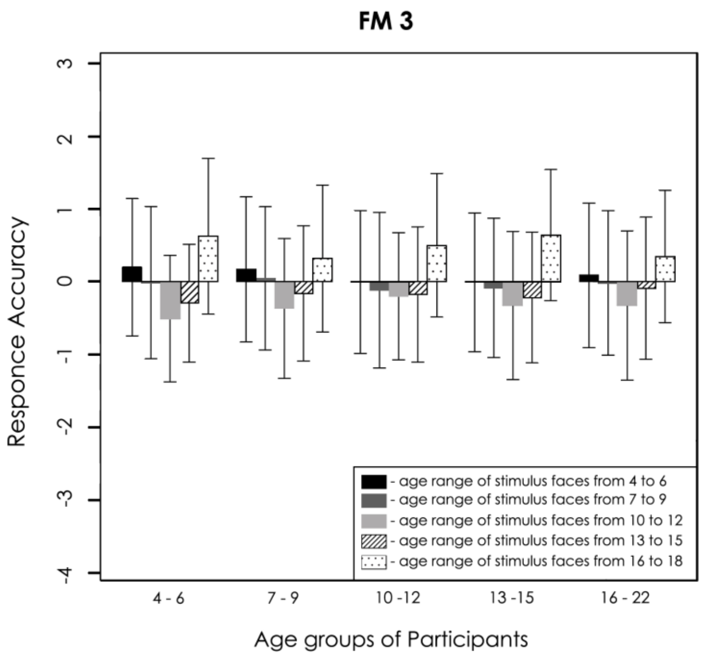

Figure A3. Average within group response accuracy across participant's age in the third block of the Acquisition curve task for different stimulus age categories. Response accuracy has been z-standardized within participant age groups.

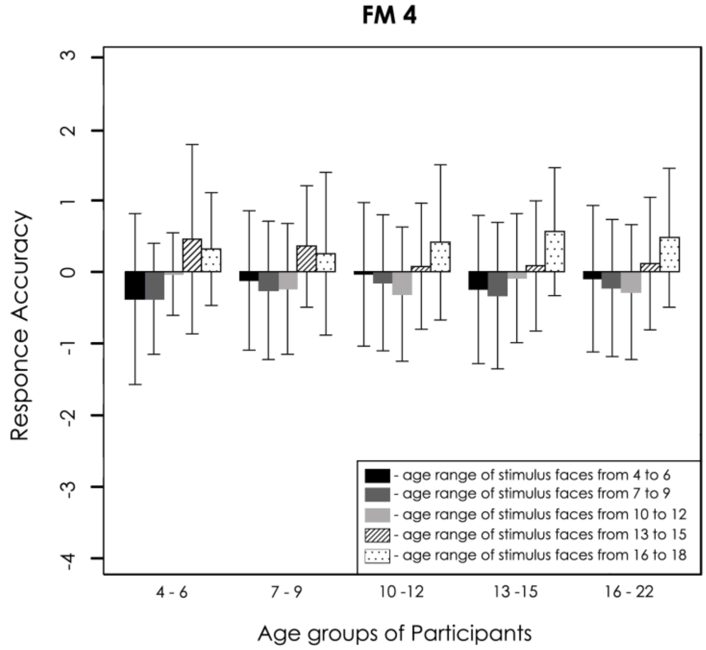

Figure A4. Average within group response accuracy across participant's age in the fourth block of the Acquisition curve task for different stimulus age categories. Response accuracy has been z-standardized within participant age groups.

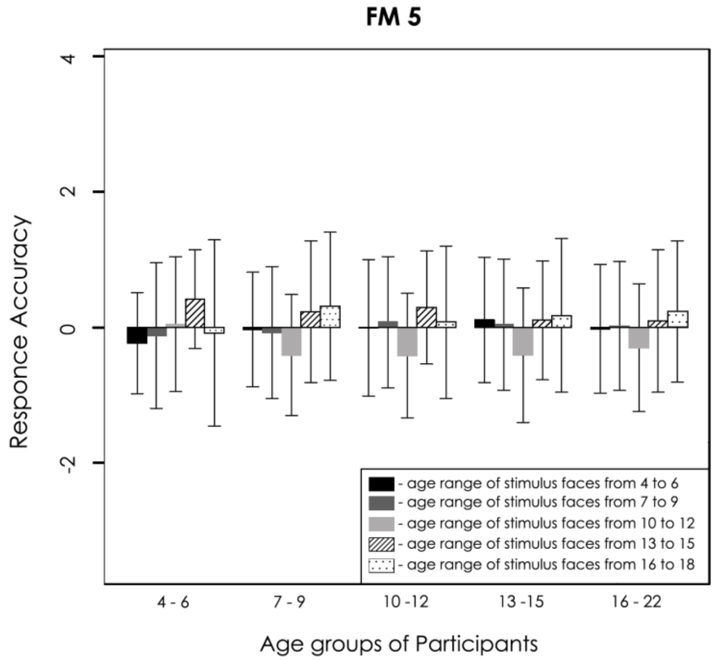

Figure A5. Average within group response accuracy across participant's age in the Decay Rate task for different stimulus age categories. Response accuracy has been z-standardized within participant age groups.

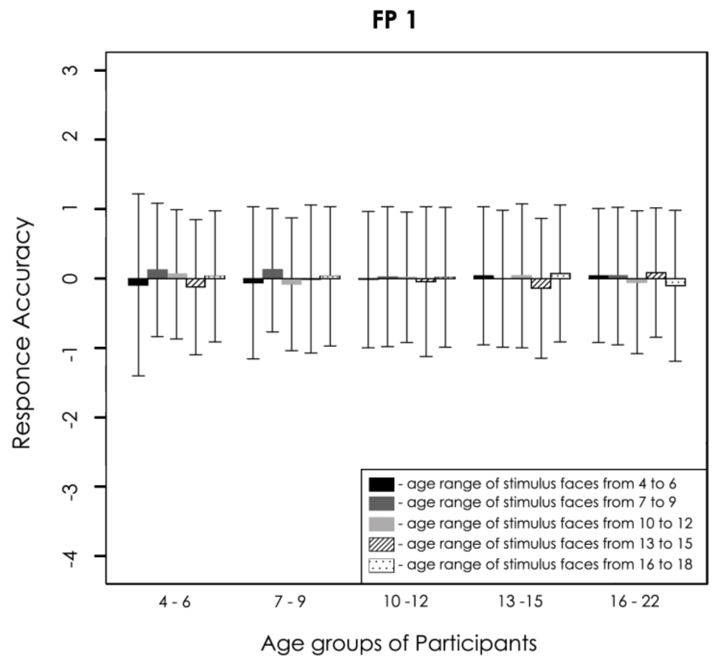

Figure A6. Average within group response accuracy across participant's age in the congruent trials in the Composite face task for different stimulus age categories. Response accuracy has been z-standardized within participant age groups.

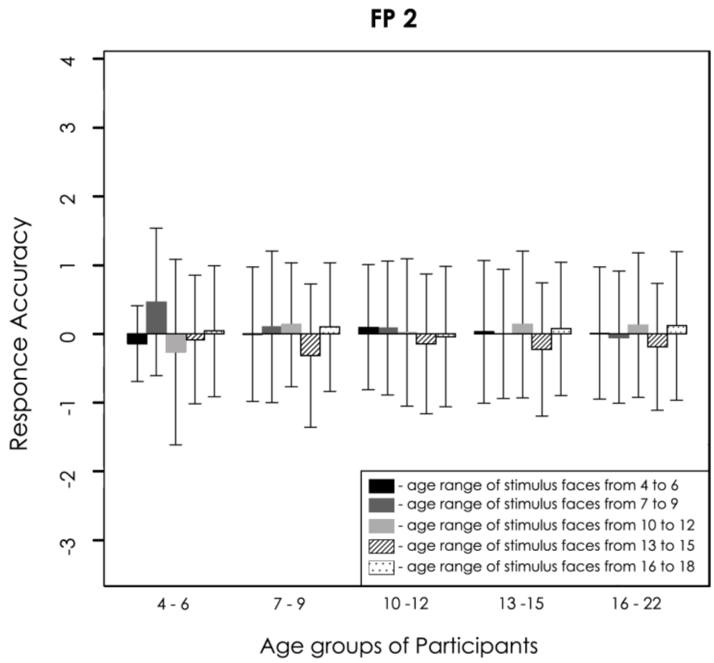

Figure A7. Average within group response accuracy across participant's age in the incongruent trials in the Composite face task for different stimulus age categories. Response accuracy has been z-standardized within participant age groups.

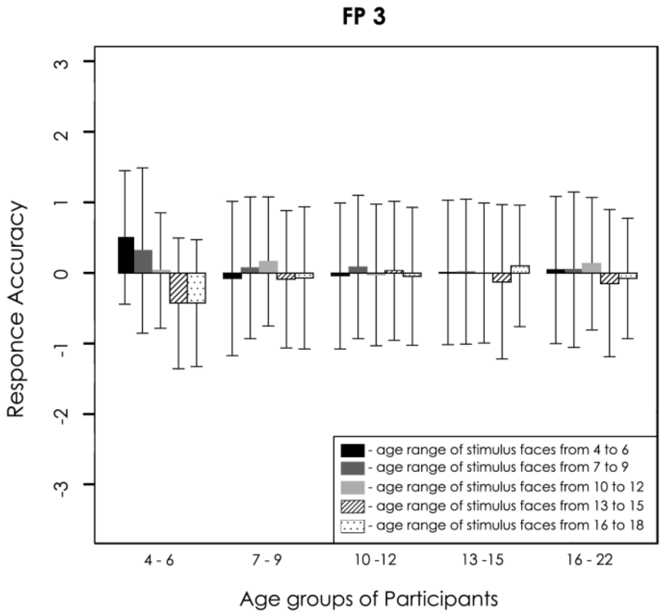

Figure A8. Average within group response accuracy across participant's age in the upright trials in the Simultaneous matching of spatially manipulated faces task for different stimulus age categories. Response accuracy has been z-standardized within participant age groups.

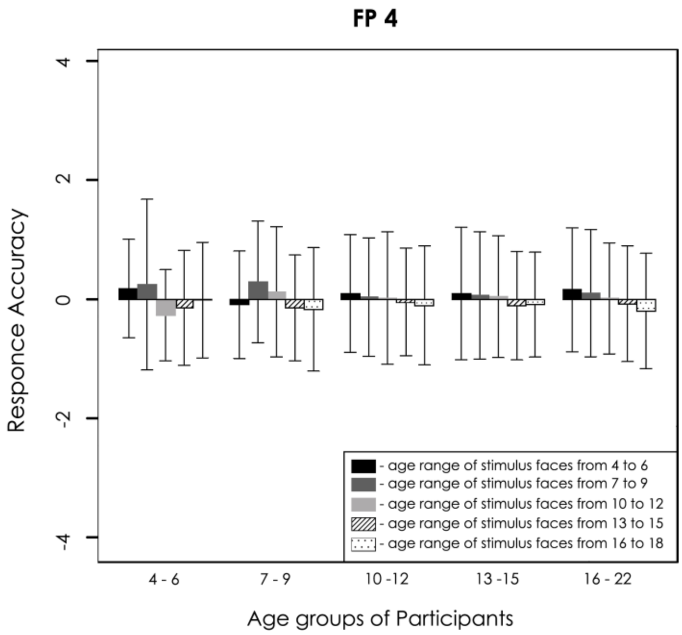

Figure A9 Average within group response accuracy across participant's age in the inverted trials in the Simultaneous matching of spatially manipulated faces task for different stimulus age categories. Response accuracy has been z-standardized within participant age groups.

Manuscript 2: Face cognition abilities across childhood and adolescence are strongly related with general cognitive functioning but become more content specific

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Abstract

Psychometric research on young adults indicates that individual differences in face cognition abilities are specific as they cannot be entirely explained through variance in general cognitive functioning and object cognition. However, it is not established whether face cognition abilities are domain-specific already in early periods of life or differentiate across childhood and adolescence. In the present study, $N = 338$ participants, aged 6 to 21 years, performed multiple tasks measuring abilities of face perception and face memory, object perception, object memory, and general cognitive functioning (i.e. figural reasoning and working memory). We estimated age and individual differences in the covariance structure of face cognition abilities and general cognitive functioning, as well as age trajectories of average face cognition performance after accounting for variance explained by general cognition. The results indicate a strong association between face cognition abilities and general cognitive functioning in early periods of life with a tendency for dedifferentiation between these abilities. However, face versus object perception and face versus object memory became more distinct across childhood and adolescence. On a theoretical level these results imply that it is necessary to consider face perception and memory as getting increasingly distinct from perception and memory for non-face objects (content-specificity); nevertheless, the level of face cognition maturation is strongly associated with the maturation of general cognitive functioning. Furthermore, age-related increase in average face cognition performance is not face-specific but can be explained by age-related increase in general cognitive functioning.

Key words: face cognition abilities, general cognitive abilities, childhood, adolescence, age differences, individual differences, construct specificity

Face cognition abilities across childhood and adolescence are strongly related with general cognitive functioning but become more content specific

Humans differ in their abilities to perceive, learn and recognize faces (e.g., Wilhelm, Herzmann, Kunina, Danthiir, Schacht, & Sommer, 2010; Wilmer, 2017). Individual differences research on face cognition (including facets of face perception and face memory) suggests that only about half of the variance quantifying individual differences between young adults can be explained through general cognitive abilities, including object cognition, working memory, reasoning, immediate and delayed memory and mental speed (Wilhelm et al., 2010). Furthermore, face cognition abilities remain to a large extent independent from general cognitive abilities through adulthood until senescence (Hildebrandt, Wilhelm, Schmiedek, Herzmann, and Sommer, 2011). But are face cognition abilities specific already early in childhood or do they differentiate from object cognition and general cognitive abilities across childhood and adolescence? Individual differences in face cognition as compared with general cognitive abilities in childhood and adolescence is not sufficiently investigated by using a multivariate task design. Experimental research on face cognition does not provide an answer to the question to which extent individual differences in face perception and face memory in early periods of the life depend on general cognitive development and whether these abilities follow an early face-specific development (for reviews, Crookes & McKone, 2009; Want, Pascalis, Coleman, & Blades, 2003; Weigelt, Koldewyn, Dilks, Balas, McKone, & Kanwisher, 2013). The relationship between face cognition and general cognitive abilities, but also object cognition may vary across age. In the present study we adopted a multivariate perspective on individual differences. We addressed the questions, whether face perception and face memory are specific abilities from early periods of life, whether they are related with general cognitive abilities in children and adolescents, and how these relations differ across age.

Current State of Research on Face Cognition Specificity during Childhood and Adolescence

Two views dominate the scientific discussion on face cognition specificity during development: First, the *face-specific development theory* or *late maturity* view proposes that infants are born with a predisposition to especially attend to faces as environmental stimuli (Morton & Johnson, 1991). During maturation face cognition abilities develop within a special face processing system along with social experiences and become qualitatively (i.e., being present) and quantitatively (in terms of performance level) adult-like in late adolescence (Carey & Diamond, 1977; Carey, Diamond, & Woods, 1980; Diamond & Carey, 1977). Subsequent studies found qualitative characteristics of face cognition (e.g., holistic processing) to be present much earlier than 10 years of age (for a review see McKone, Crookes, Jeffery, & Dilks, 2012). Therefore, the *face-specific development theory* was reframed. In its present form, the theory argues for late quantitative maturity assuming skills to be present early on, but to reach full adult levels in late childhood or adolescence (for a review see Weigelt et al., 2013).

Second, within the framework of the *theory of general cognitive development,* or *early maturity* view, researchers suggested that the early preference for faces is not due to a congenital predisposition to attend facial stimuli (Turati, Simion, Milani, & Umilta, 2002). Instead it was argued that faces are not specific stimuli but prototypical top-heavy objects that are easily accessible for the immature visual system of the child. In general, this framework assumes that face cognition abilities can reach adult-like levels by the age of five years or even earlier, both qualitatively and quantitatively, depending on the maturity level of other abilities (e.g., memory, selective attention; for a review see Crookes & McKone, 2009; Weigelt et al., 2013).

Later, an alternative position was proposed. In a study with children aged between five and 10 years and young adults, Weigelt et al. (2013) showed diverse trajectories of maturation for face perception as compared with face memory. On the one hand, face memory trajectories followed predictions of the late maturity theory, with domain-specific development for faces occurring until the age of 10 years. That is, a slower development was observed for memorizing faces as compared with a series of non-face object classes. On the other hand, perceptual discrimination followed the predictions of the early maturity theory, with no domain-specific development for faces. That is, there were similar developmental trajectories for faces and non-face objects. These findings seemed to integrate both previous positions and were consistent with the basic dissociation between face perception and face memory suggested by functional and neuroanatomical models of face cognition and psychometric research (e.g. Bruce & Young, 1986; Haxby, Hoffman, & Gobbini, 2000; Wilhelm et al., 2010).

Thus, the current state of theorizing on the specificity of face cognition in childhood and adolescence embraces two conflicting views and an attempt to combine these positions. However, there is no multivariate research quantifying the extent to which face perception and face memory depend on general cognitive development in early periods of the life and whether these abilities show early face-specific development. There are several possible explanations for the controversial views in the literature. First, there is disagreement on the appropriate stimulus material – children faces (Anastasi & Rhodes, 2005; Flin, 1985a; Hills & Lewis, 2011; Hills, 2012) versus adult faces (Chung, 1977; Picci & Scherf, 2016). Second, hitherto published data only describe age trajectories based on average performance, captured by single tasks and not at the level of latent variables quantifying face cognition-specific variance. Furthermore, researcher disagree on the paradigms to be used for measuring face cognition abilities (e.g., for the measurement of face perception see Burton, Schweinberger, Jenkins, & Kaufmann, 2015; Macchi-Cassia, Turati, & Schwarzer, 2011; Richler & Gauthier, 2014; Rossion, 2013). Finally, in many studies there are problems in statistical analyses due to rather arbitrary assignment of age groups. By clustering participants into age groups, individual differences within age cohorts are ignored (Hildebrandt, Lüdtke, Robitzsch, Sommer, & Wilhelm, 2016).

An Individual Differences Perspective on Face Cognition Specificity

Although individual differences in the abilities to perceive, learn and recognize faces were acknowledged early on, systematic investigations of the structure of these differences emerged only late. Wilhelm and co-workers (e.g., Hildebrandt et al., 2010; Wilhelm et al., 2010) were the first to investigate the structure of individual differences in face cognition and the association of these abilities with general cognitive functioning by applying a multivariate approach. They followed several psychometric principles in their studies that are also relevant for the present research.

First, they adhered to the dissociation between face perception and face memory, suggested in functional and neuroanatomical models of face cognition (Bruce & Young, 1986; Gobbini & Haxby, 2007; Haxby, Hoffman, & Gobbini, 2000). These models postulate that face cognition processes are associated with different brain systems. For example, face perception is carried out in the occipital gyrus and the lateral fusiform gyrus whereas face recognition is mainly associated with the fusiform face area and the anterior temporal lobe (Gobbini & Haxby, 2007; Kanwisher, McDermutt, & Chun, 1997).

Second, Wilhelm and coworkers (2010) used multiple tasks for measuring face perception and face memory abilities. This approach is especially relevant for the present work as well, because a multivariate approach allows to account for measurement error and the specificity of the measurement method. Thus, abilities can be studied at the level of latent constructs and the findings can be generalized across different tasks that are conceivable assessment tools of face cognition abilities.

A third principle is the strict distinction between tasks measuring speed and tasks measuring performance accuracy (see also Carroll, 1993; Furneaux, 1952). Speed performance is parameterized as time required per correct response in tasks with a low level of difficulty.

Accuracy performance is parameterized as the number of correct responses in tasks that are sufficiently difficult to preclude a substantial proportion of the population to solve all items correctly even if processing time is unrestricted.

Based on data from more than 300 participants, Wilhelm and co-workers (2010) proposed a three-factorial model of structure of individual differences in face cognition abilities. In this model, face perception accuracy is understood as the ability to perceive faces as a whole and to distinguish facial features and their configuration; face memory accuracy is the ability to encode, store and retrieve faces from long-term memory; and the speed of face cognition is the ability to quickly perceive and recognize faces. Furthermore, Wilhelm et al. (2010) showed that in young adulthood only half of the variance in face cognition abilities can be explained by other cognitive abilities, such as object perception and memory, immediate and delayed memory for words, numbers and abstract figures, working memory and reasoning. These findings support the idea that face cognition abilities in young adults are distinct from general cognition and, hence, specific.

Face Cognition remain Specific from Young Adulthood to Old Age

An influential theory in research on cognitive development is the differentiation–dedifferentiation hypothesis (e.g., Balinsky, 1941; Garrett, 1938; Garrett, 1946; Tucker-Drob, 2009). This hypothesis holds that across early periods of life cognitive abilities gradually differentiate from an amorphous general cognitive ability, whereas late in life they become reintegrated, or dedifferentiated again. However, early research on the differentiation–dedifferentiation hypothesis was criticized and called into question because of methodological limitations (see for review, Hildebrandt et al., 2010). A number of authors, such as Cunningham (1981), Lindenberger & Baltes (1997), Schaie, Willis, Jay, & Chipuer (1989), Tucker-Drob & Salthouse (2008), and Tucker-Drob (2009) refuted the differentiation–dedifferentiation hypothesis by showing invariance of the structural configuration of cognitive abilities up to very old age.

Hildebrandt et al. (2011) addressed the dedifferentiation hypothesis for the case of face cognition across the adult lifespan. Following reports about restrictions/refutation of this hypothesis they expected that face cognition abilities – due to their specific dependency from everyday social experiences – would maintain their distinctness as compared with general cognitive abilities (general cognitive functioning, mental speed, immediate and delayed memory) across the adult lifespan. Indeed, they found no factorial dedifferentiation between face cognition abilities and general cognitive abilities. Hence, face cognition remains a specific human ability compared with general cognition from young adulthood to old age.

Aims and Hypotheses of the Present Study

As discussed above, previous studies on the specificity of face cognition abilities in childhood and adolescence provided inconsistent results on whether face cognition develops as a part of the general cognitive system and differentiates later, or whether it is specific already during early periods of life (for a review see Crookes & McKone, 2009; Want et al., 2003; Weigelt et al., 2013). From an individual differences perspective, within the framework of the differentiation-dedifferentation hypothesis the specificity of face cognition has been only investigated across the adult lifespan (potential dedifferentiation in late periods of the life; Hildebrandt et al., 2011). So far, the differentiation-dedifferentation hypothesis has not been tested for face cognition within the early lifespan. Hence, it is not known whether the structure of face cognition and its specificity are age-invariant and in how far they can be explained by general cognitive functioning and object cognition across childhood to young adulthood.

In general, the present study aimed was to follow the approaches established by Wilhelm et al. (2010) and Hildebrandt et al. (2011) for the domain of face cognition research, and apply it to the question of face cognition specificity in children and adolescents. We therefore administered multiple tasks measuring face cognition and general cognition, used face stimuli of various ages, tested a large sample of children and adolescents aged between 6 to 20 years;

for these data we estimated age and individual differences in the covariance structure of face cognition abilities as compared with general cognitive functioning. After accounting for interindividual variability in general cognition we parameterized variance in face cognition at the level of latent variables in order to generalize across specificities of assessment methods.

We tested the differentation-dedifferentation hypothesis (Balinsky, 1941; Garrett, 1938; Garrett, 1946; Tucker-Drob, 2009) for the case of face cognition across the early lifespan. We predicted face cognition to be a specific ability and a basic facet of social intelligence (Hildebrandt et al., 2011; Wilhelm et al., 2010). In terms of the *face-specific developmental theory* we expected face cognition abilities to be specific already in youngest age. Hence, no differentiation between face cognition and general cognitive abilities should be observed from early school age to young adulthood; the abilities should follow parallel developmental trajectories. This expectation is consistent with restrictions/refutation of the differentation-dedifferentation hypothesis in recent studies (see for review, Tucker-Drob, 2009).

Further, we investigated age-related differences in face cognition performance after accounting for the variance explained by general cognitive functions. Following the *face-specific developmental theory*, we expected performance in face cognition abilities to become adult-like only late, that is, approaching young adulthood and that specific face cognition maturation cannot be entirely explained by developmental improvements of general cognitive functions.

Method

Sample

There were $N = 338$ children, adolescents and young adults aged between 6 and 21 years (50% females) involved in the study. They were recruited in Berlin's primary schools, high schools, and vocational schools. The study received approval of the Ethics Committee of the Department of Psychology, Humboldt-Universität zu Berlin (Nr. 2013-44R) and by the Senate of the State of Berlin. Participants' distribution according to age and gender is shown in Table 1 of the Appendix (Table A1).

Only complete datasets (including all trials of all tasks) were analysed. Out of the N = 338 participants who started the study there were 284 complete datasets available for analyses. Missing data were due to drop outs (N = 10) or technical problems with some of the measures.

Stimuli and Apparatus

A total of 460 frontal view colour portraits of girls and boys aged between 4 and 18 were taken under standardized conditions with respect to luminance, distance, camera settings, and instructions for the models. All portraits showed neutral expressions and did not display distinct features or adornments, such as glasses, moles, salient make-up, or other facial marks. Further, we excluded all face-external features such as hair, ears, and clothing by fitting the faces into a vertical ellipse of 300 by 200 pixels (7.6 * 5.1 cm); please see Figure 1 in the Appendix (A1) for examples. For all face stimuli we obtained ratings of distinctiveness from 12 young adults (8 females) based on the procedure by Wickham, Morris and Fritz (2000). Rather non-distinct face stimuli were selected for the memory tasks because they are more difficulty to recognize. Girls and boys face stimuli were presented equally often in all tasks.

Object stimuli were 460 pictures of houses (Fig. A2 in the appendix). Analogously to the face stimuli, houses varied in drawing style corresponding to face age. There were three types of houses: either cartoon-like in style or more realistic. Cartoon-like houses were designed by an artist for the present study. The fourth type of houses were photographs of real houses rendered with Adobe Photoshop Elements 12 to be somewhat cartoon like. The fifth type were photographs of houses, obtained from different sources. The size of all house stimuli was edited to the same format as for faces (300*200 pixels, corresponding 7.6*5.1 cm on the screen). Stimuli were presented on notebooks (Lenovo Thinkpad, Modell E330), with 13.3 inch monitors (resolution 1366*768). All tasks were programmed in PsychoPy v1.82.01 (Peirce, 2007).

Tasks

Composite faces task. We used a version of the composite task full design, developed for adults by Meinhardt-Injac, Persike, and Meinhardt (2014). We adapted the task for children and adolescents. In each trial of this task two composite-faces (upper and lower face part from two different identities lumped together) were presented sequentially. The second composite-face was displayed together with a green arch with fingers on each side, presented at the top or bottom of the face. The fingers indicated which half of the face was relevant for the answer (for an example of a trial sequence see Fig. A3 in the appendix). Participants were asked to indicate whether the cued half of the second face was the same or different as compared with the corresponding half of the first presented composite face. Congruent and incongruent trials were balanced in their number. Figure A4 displays all experimental conditions implemented in the task, including the congruency variation.

Simultaneous matching of spatially manipulated faces with upright and inverted conditions. This task was developed for adult participants by Herzmann, Danthiir, Schacht, Sommer, and Wilhelm (2008) and Hildebrandt, Sommer, Wilhelm, and Herzmann (2010). Here we adapted the task for children and adolescents. Participants indicated whether two simultaneously presented upright or inverted faces were the same or different. Two presented faces were derived from the same picture. In 50% of the trials the presented portraits were identical and in the other half of the trials one of the portraits was altered by changing a spatial relationship between the features of the original face. The spatial manipulations varied in extent, and hence in their perceptual difficulty. Changes were as follows: (1) moving the eyes up or down by 5 or 7 mm; (2) moving the eyes together or apart by 5 or 7 mm; and (3) moving the mouth up or down by 3.5 or 5 mm. In Figure A5 all levels of difficulty are displayed. These levels of difficulty were chosen on the basis of a pilot study with 100 children and adolescents. Figure A6 displays an example of the trial sequence.

Acquisition curve. This task measuring the encoding and recognition of faces was developed for adult participants by Herzmann et al. (2008) and Hildebrandt et al. (2010). We adapted the task for children and adolescents. It included a study, an intermediate task, and a recognition phase. In the study phase, participants were expected to memorize 15 faces, presented simultaneously in a matrix for one minute. In the intermediate task participants were expected to decide as quickly as possible whether two simultaneously presented series of letters, numbers, or symbols are the same or different. In the recognition phase each learned face was shown twice, each time paired with a different novel face. Participants were asked to indicate the learned face in each trial. The task included four procedurally identical blocks of 30 trials each, involving a total of 60 learned faces.

Decay rate. This task aims to measure the delayed recognition of learned faces and it was developed for adult participants by Herzmann et al. (2008) and Hildebrandt et al. (2010). Here it was adapted for children and adolescents and conducted at the end of the testing session. Participants were to indicate the faces, which they had learned during the face memory task described above. Sixty learned faces were presented successively, paired with novel distractors.

Object cognition tasks. In order to measure perception and memory for houses we used the same paradigms as described above for faces but replaced faces by house stimuli. The composite house task and the simultaneous matching of spatially manipulated houses with upright and inverted conditions were shorter as compared with their face counterparts because for house stimuli stimulus sex did not have to be varried.

Working memory. The working memory task was adapted from Dirk & Schmiedek (2015) and Könen, Dirk & Schmiedek (2015). Participants were asked to remember positions and movements of colourful monsters within a 4*4 grid. At the beginning of a trial, two (load 2) or three (load 3) monsters with different colours appeared for three seconds at different positions of the grid, followed by a 500 ms blank screen. Participants had three seconds to remember the starting position of each monster. Subsequently, they were asked to focus on arrows presented in a colour corresponding to one of the monsters appearing in the center of the grid. The arrows indicated the direction in which a corresponding monster (matched by colour) changed its position in the grid. Each monster made only one step within the grid in one of the eight following directions: left, right, up, down, or in the diagonals. If a monster's position was at the margin of the grid, no further movement towards the margin was designated by the program. The time to memorize the direction of position changes was limited to 2.5 s. At the end of a trial participants indicated the last position of each monster by mouse click into the corresponding field. Load 2 and Load 3 were used equiprobably.

Figural fluid intelligence. We measured fluid intelligence with four paper-pencil versions of the figural part of the Berlin Test of Fluid and Crystalized Intelligence (BEFKI GC-K (Schipolowski, Wilhelm, Schroeders, Kovaleva, Kemper, & Rammstedt, 2013; Wilhelm, Schroeders, & Schipolowski, 2014)), adapted for Grade 1 to 4, 5 to 7, 8 to 10, and 11 to 12. Within this task participant were asked to continue the logical chain of three figures, which progressed according to certain rules. There were two further steps to be sustained by choosing from three given alternatives each (cf. Fig. A9). Participants had limited time (14 min.) to complete the 16 items of this test.

Procedure

The study included two sessions carried out on different, usually successive, days. On the first day children and adolescents received stickers with their identification numbers and were assigned to one of two groups tested in different rooms. Group 1 started with the demographic questionnaire, including sex, age and school performance and completed the fluid intelligence test. This session lasted about 30 min. There were no breaks during this session. Group 2 worked at the computerized tasks, assessing, face and house perception, working memory, memory for faces and houses. This session took about 2,5 hours, including breaks.

On the second test day the groups switched sessions. Each group worked with two proctors who gave age-appropriate instructions.

Scoring and data treatment

From the above described tasks we derived as series of indicators to be used in Structural Equation Modeling (SEM). We calculated four indicators for face perception and correspondingly four for object perception. The indicators FP1, OP1 and FP2, OP2 represent proportion of correct responses achieved in the congruent and incongruent conditions, derived from the Composite faces and houses tasks, respectively. The indicators FP3, OP3 and FP4, OP4 represent proportion of correct responses in the upright and inverted conditions, derived from the Simultaneous matching of spatially manipulated faces and houses. For memory abilities we derived ten indicators: FM1, FM2, FM3, FM4 and OM1, OM2, OM3, OM4, representing proportions of correct responses in four blocks of the Acquisition curve tasks for faces and objects and FM5 and OM5 representing performance in the Decay rate tasks. From the working memory task we derived two indicators: WM1 and WM2, representing proportion of correct responses in load 2 and load 3 condition of the task, respectively.

As mentioned, the fluid intelligence task consisted of four test versions designed for different age groups. Each version included linking items which were presented to all participants, independently of their age. The scoring was based on estimated person parameters from the age-specific item pools, along with the mutual items that warrant the linking and establish comparable scale of the person parameters across the age groups. First, we applied the Rasch Model (Rasch, 1960) using the R package Supplementary Item Response Theory Models (sirt; Robitzsch, 2016) in order to estimate person parameters. The Rasch Model was estimated with the Martin-Loef-Test (Martin-Loef, 1973) using the R package Extended Rasch Modeling (eRm; Mair, Hatzinger, Maier, & Rusch, 2016). Finally, we carried out Haberman (2009) linking using the sirt package (Robitzsch, 2016), which has the advantage that it allows using many test forms simultaneously and performs well for differently calibrated items across age groups. Finally, from this task we derived two indicators Gf1 and Gf2, representing person parameter based on two halves of items out of the 16 included in the test. Figure A10 illustrates the assignment of the trials to indicators according to the tasks. There were no outliers in univariate distributions of the indicators.

Statistical Analysis

We used Local Structural Equation Modeling (LSEM; Hildebrandt, Lüdtke, Robitzsch, Sommer, & Wilhelm, 2016), which is a non-parametric extension of moderated structural equation models (SEM, e.g., Kline, 2011). We used the sirt package (Robitzsch, 2016) implemented in the R environment (R Core Development Team, 2017). LSEM applies a kernel function for weighting observations around continuously defined focal values of a context variable, like age, and repeatedly fits SEMs along this moving weighting window (Gasser, & Müller, 1984; Gasser, Gervini, & Molinari, 2004; Hülür, Wilhelm, and Robitzsch, 2011). Observations on each focal age – defined for the present study in steps of one year from 8 to 20 years – receive a maximum weight. Sample weights fall off symmetrically with increasing distance of an observation from the focal value. Thus, we fitted the measurement model of face cognition abilities and general cognitive functioning with changing sample weights across 13 focal points from age 8 in steps of one year until the age of 20. LSEM parameter functions across age are presented as results. To test parameter changes across age inferentially, we used a permutation test (Hildebrandt et al., 2016) against the null hypothesis that a given SEM parameter is constant across age. Due to space constraints, for details on all these methods we refer to the statistical literature indicated above.

Results

Results are derived from five estimated SEMs. In a first step, we simultaneously investigated the structure of face and object perception (Model 1) and of face and object memory (Model 2). Second, we tested the structure of individual differences regarding the predictor variables that will be used to investigate specificity of face cognition abilities. That is, we analysed the latent structure of object perception and object memory along with general cognitive functioning (Model 3). Next, we established the structural relationship of face cognition and general cognitive functioning (Model 4), which we then tested for age differentiation using LSEM. Finally, Model 5 tested age-related performance differences in face cognition after accounting for general cognitive functioning. That is, we tested face-specific performance differences across childhood and adolescence.

Model 1: The Structure of Face and Object Perception

Model 1 consisted of two correlated factors of face and object perception, each measured by four indicators (FP1-FP4 and OP1-OP4, see description in the Scoring and data treatment section). The fit of Model 1 was reasonable: $\chi 2$ (14) = 97.551, p = .000, CFI = .939, RMSEA = .145, SRMR = .035. Factor loadings ranged between .73 and .88. Unexpectedly, the correlation between the latent factors of face perception and object perception was statistically not different from unity ($r_{FP/OP}$ = 1). Further explorations of the covariance structure including task specific latent variables for face and house stimuli showed that the very high correlation between the face vs. object factors was due to the very high correlation observed between the Composite face task and the Composite house task (see Table 1). This finding indicated that the Composite task does not seem to specifically measure face perception. Therefore, the Composite tasks will not be included in the further model of face cognition when testing its specificity across age. At this stage we conclude that the composite task is measuring a general ability not depending on stimulus content.

Table 1. Correlations between the corresponding face and house perception tasks modelled as task specific latent variables.

	CFT	CHT	SmSMF	SmSMH
CFT	1.00			
CHT	**1.00**	1.00		
SmSMF	.722	.745	1.00	
SmSMH	.500	.497	.703	1.00

Note. CFT – Composite face task; SmSMF – Simultaneous matching of spatially manipulated faces; CHT – Composite house task; SmSMH - Simultaneous matching of spatially manipulated houses.

Model 2: The Structure of Face and Object Memory

Model 2 consisted of two correlated latent factors representing face and object memory, each measured by five indicators (FM1-FM5 and OM1-OM5, see description in the Scoring and data treatment section). The fit of Model 2 was reasonable: $\chi 2$ (34) = 147.109, p = .000, CFI = .920, RMSEA = .108, SRMR = .054 and factor loadings ranged between .54 and .80. The correlation between the two latent factors in the overall sample, irrespectively of age, was high but not perfect (FM/OM = .80). We can thus conclude that the overlapping variance between FM and OM is 64%, suggesting that the memory for faces is not isomorph with general object memory.

Model 3: The Predictor Model

The predictor model (Model 3; Fig. 1) consisted of three orthogonal factors, including object perception (measured by the indicators OP3 and OP4, which turned out not to be perfectly correlated with their face counterparts), object memory (measured by indicators OM1 to OM5) and general cognitive functioning, measured by all indicators included in the model (Gf1, Gf2, WM1, WM2, OP1, OP2, OP3, OP4, OM1, OM2, OM3, OM4, OM5), and defined by working memory and reasoning. The fit of Model 3 was reasonable: $\chi 2$ (57) = 103.002, p = .000, CFI = .974, RMSEA = .053, SRMR = .043. Factor loadings ranged between .24 and .83 and were all statistically significant (see Table 2). Lower loadings were observed for the nested factors which is expected in such a structural representation in which nested factors are modelled under a general factor. Residual covariances between Gf1 and Gf2, respectively WM1 and WM2, representing method specificity were .67 and .59.

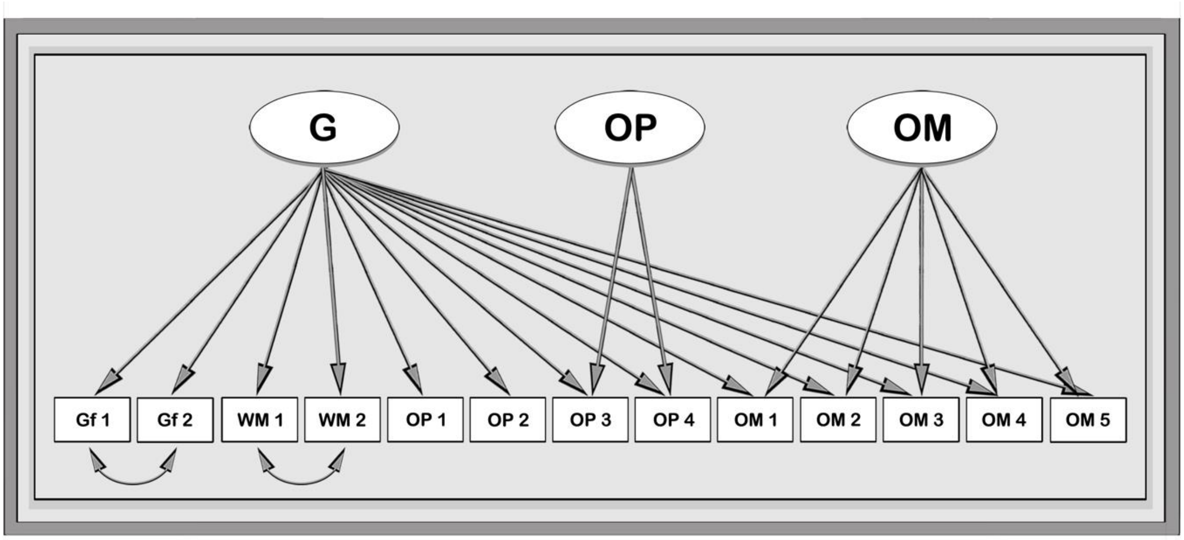

Figure 1. Schematic representation of the predictor model used to test specificity of Face Cognition abilities. The model includes the following factors: Object Perception (OP), Object Memory (OM), and General Cognitive Functioning (G). For a description of the indicators see the Scoring and data treatment section.

Table 2. Factor loadings observed in the predictor model

	Gf1	Gf2	WM1	WM2	OP1	OP2	OP3	OP4	OM1	OM2	OM3	OM4	OM5
G	.496	.562	.573	.654	.682	.839	.446	.382	.468	.539	.551	.565	.540
OP	-	-	-	-	-	-	.707	.761	-	-	-	-	-
OM	-	-	-	-	-	-	-	-	.514	.573	.551	.519	.242

Note. G - General Cognitive Functioning, OP - Object Perception, OM - Object Memory. For a description of indicators see the Scoring and data treatment section.

Model 4a: Testing Specificity of Face Cognition Abilities

The model of face cognition abilities in their relation with general cognitive functioning and object cognition (Model 4a; Fig. 2) postulates two correlated face cognition factors (face perception and face memory) that are related with the three orthogonal predictors of object perception, object memory, and the G factor depicted in Fig. 1. The fit of Model 4a was reasonable: $\chi2$ (155) = 402.763, p = .000, CFI = .923, RMSEA = .075, SRMR = .064. Factor loadings ranged between .21 and .89 (see Table 3). Residual covariances between Gf1 and Gf2, respectively WM1 and WM2 were .67 and .59. Associations between face perception and general cognitive functioning and between face perception and object perception were significant (latent regression coefficients were .75 and .38, $p < .001$). Associations between face memory and general cognitive functioning and between face memory and object memory were significant as well (latent regression coefficients were .70 respectively .45, $p < .001$). There were no statistically significant associations between face perception and object memory and face memory and object perception.

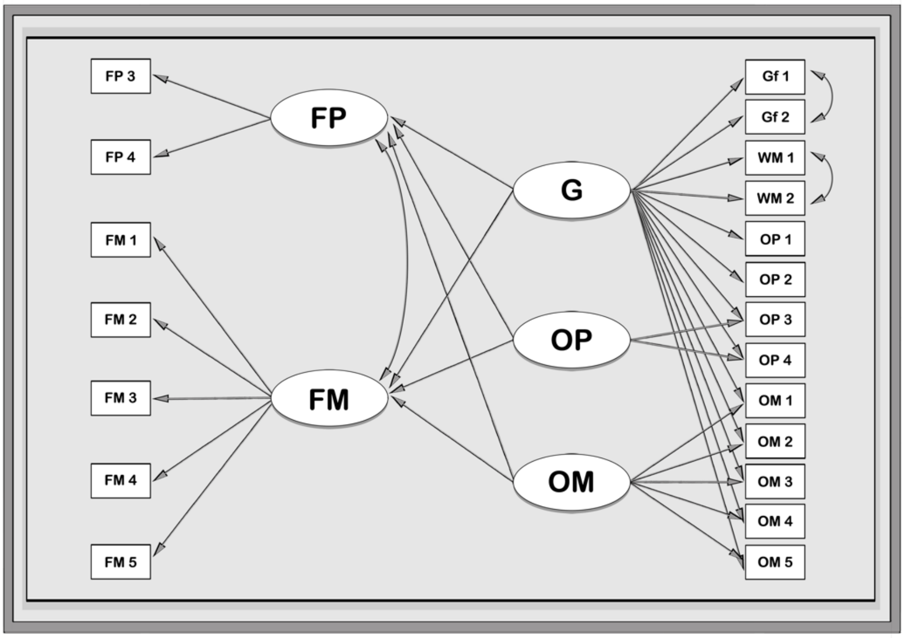

Figure 2. Schematic representation of the model testing specificity of Face Cognition above General Cognitive Functioning and Object Cognition. Face Perception (FP); Face Memory (FM); General Cognitive Functioning (G); Object Perception (OP); Object Memory (OM). For a description of the indicators see the Scoring and data treatment section.

Table 3. Standardized factor loadings estimated in the Model of Face Cognition and General Cognitive Functioning (Model 4a)

	Gf1	**Gf2**	**WM1**	**WM2**	**OP1**	**OP2**	**OP3**	**OP4**	**OM1**	**OM2**	**OM3**	**OM4**	**OM5**	**FP3**	**FP4**	**FM1**	**FM2**	**FM3**	**FM4**	**FM5**
G	.500	.573	.566	.653	.688	.830	.439	.390	.469	.546	.560	.563	.548	-	-	-	-	-	-	-
OP	-	-	-	-	-	-	.704	.765	-	-	-	-	-	-	-	-	-	-	-	-
OM	-	-	-	-	-	-	-	-	.570	.495	.830	.468	.217	-	-	-	-	-	-	-
FP	-	-	-	-	-	-	-	-	-	-	-	-	-	.469	.546	-	-	-	-	-
FM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.767	.791	.765	.771	.615

Note. G - General Cognitive Functioning; OP - Object Perception; OM - Object Memory; FP – Face Perception; FM – Face Memory; WM – Working Memory.

Model 4b: Age differentiation/dedifferentiation tested with LSEM

As next we tested age differentiation of the structure of individual differences established in Model 4 based on the entire age range by using the LSEM approach. We inspected model fit indices with respect to their invariance across childhood and adolescence. Figure 3 displays the RMSEA, CFI and SRMR indices of fit, estimated at each focal value of age. Taking all three fit indices together, we can conclude that the model fit was constant and satisfactory at all focal age points.

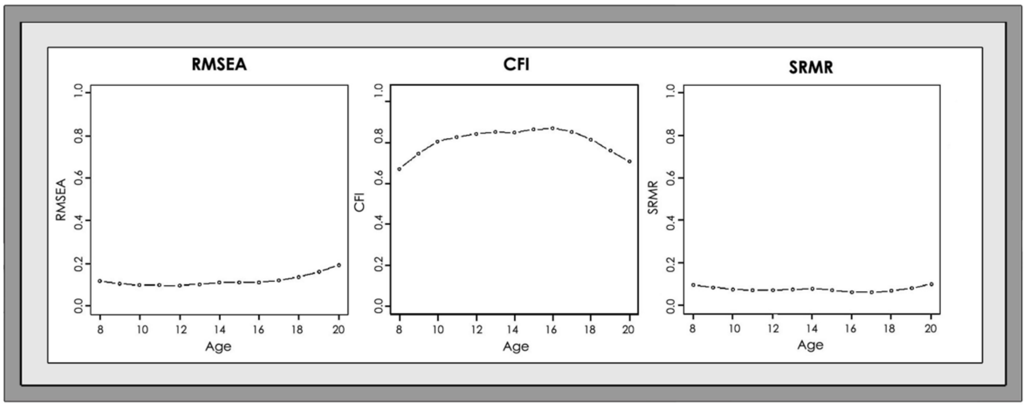

Figure 3. LSEM estimated age gradient of fit indices across age. CFI = comparative fit index (should be above .90 to indicate acceptable fit); RMSEA = root mean square error of approximation (should be below .08 to indicate acceptable fit); SRMR = standardized root mean square residual (should be below .08 to indicate acceptable fit).

Estimated factor loadings along the age-weighted focal models are plotted in Figures A11A to A11E in the appendix. They demonstrate stability of factor weights for both indicators of face perception and a slight increase of factor loadings for most indicators of face memory across age. There is a less clear picture regarding the trajectory of factor loadings in case of the indicators for object perception and object memory. The loadings of the OP3 indicator apparently indicate age-related decrease, whereas the loadings of the OP4 indicator increased across age. The loadings for the first two indicators of face memory (OM1 and OM2) are numerically invariant, whereas the three others (OM3, OM4, OM5) show a slight increase across age. Most indicators of general cognitive functioning showed an increase in their G loadings across age.

As shown in Figure 4 the relationship between face perception and face memory, controlled for general cognitive functioning, increased until the age of 12, followed by a decrease. Figure 5 shows the regression weights between face cognition abilities and its predictors included in the model (see Fig. 2). The associations between face perception and other factors differed in specific ways across age. There was no association between face perception and object memory across the entire age range. The association between face perception and object perception decreased with age, indicating differentiation. However, the association between face perception and general cognitive functioning increased with age. A similar picture appears in case of face memory, which did not show an association with object perception. The association of face memory with object memory decreased with age, indicating differentiation, but its association with general cognitive functioning increased with age.

Figure 6 displays results of the permutation test (with 500 permutation samples) conducted to assess whether the age gradients of the associations described above are statistically substantial. Permutations were carried out separately for the perception-related and the memory-related parts of the model shown in Figure 2. This model split was necessary for inferential testing because the complexity of the entire model caused convergence problems in some of the permutation samples. The pointwise p-values in Figure 6 along with the plotted test result, indicating whether a parameter estimate at a certain age point differs from the average parameter estimate across the entire age range, revealed the following. 1. Descriptively (Fig. 5), the association between face perception and object perception decreased with age; the corresponding pointwise p-values (Fig. 6A) indicate a statistically significant decrease of the parameter in the age range of 8 to 11 years and 15 to 19 years. 2. Figure 5 shows an increase of the association between face perception and general cognitive functioning across age; the pointwise p-values indicate a statistically significant increase of the parameter in the age range of 8 to 10 years and 15 to 19 years (Fig. 6B). 3. The association between face memory and object memory descriptively also decreased with age (Fig.5); the corresponding pointwise p-

values indicate a statistically significant decrease of the parameter at the age of 11 years as compared with the average parameter estimate across age (Fig. 6C). 4. Finally, Figure 5 shows the association between face memory and general cognitive functioning to increase with age as well as perception; the pointwise *p*-values indicate a statistically significant increase of the parameter in the age range of 9 to 12 years and 15 to 19 years (Fig. 6D).

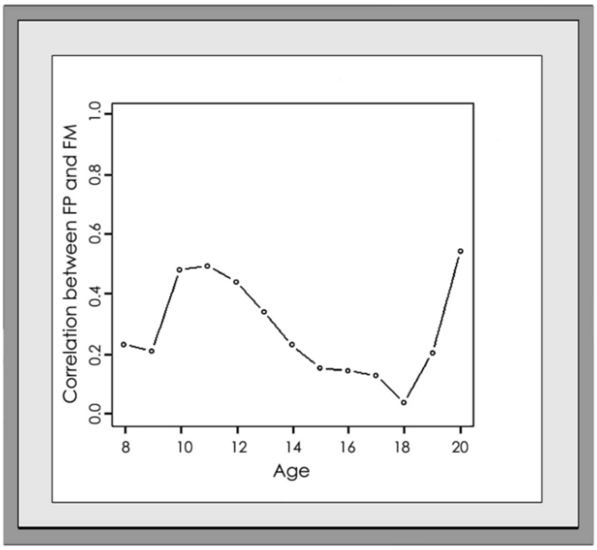

Figure 4. Correlations between face perception and face memory (FP-FM) across age.

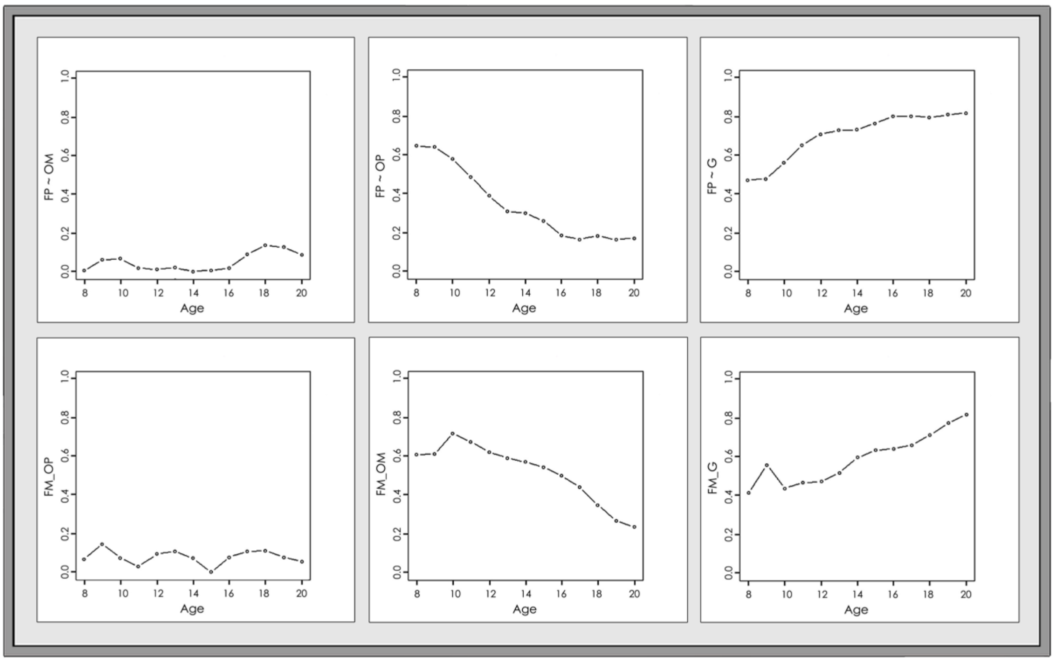

Fig. 5. LSEM estimated associations between face perception and object memory (FP-OM), face perception and object perception (FP-OP), face perception and general cognitive functioning (FP-G), face memory and object perception (FM-OP), face memory and object memory (FM-OM), and face memory and general cognitive functioning (FM-G) across age.

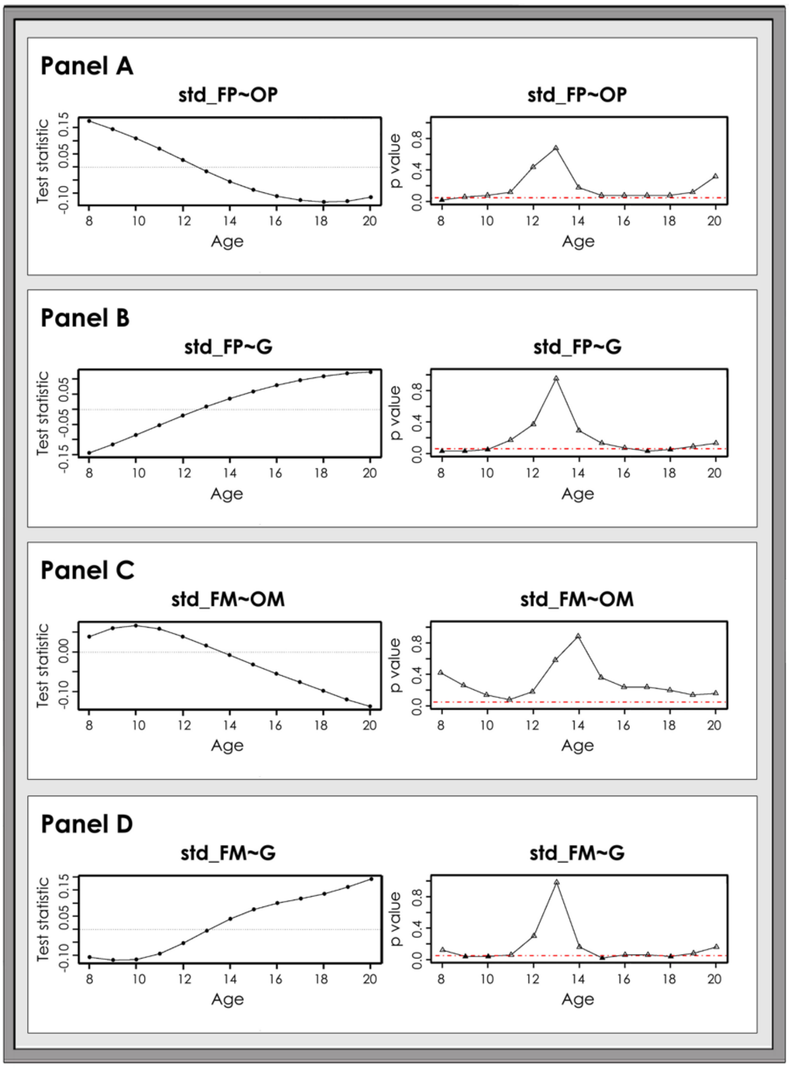

Fig. 6. Test statistics (left side) and pointwise *p*-values (right side) provided by the permutation test investigating whether associations between latent factors deviate from the average association across age. Panel A. Associations between face perception and object perception (FP-OP). Panel B. Associations between face perception and general cognitive functioning (FP-C). Panel C. Associations between, face memory and object memory (FM-OM). Panel D. Associations between and face memory and general cognitive functioning (FM-G). If a parameter at a certain focal point of age deviates from the average gradient, the *p*-value will appear below the boundary represented by a dotted red line in the right side of the figure. Additionally, statistically significant deviations of pointwise tests are marked by solid triangles.

Model 5: Age-Related Differences in Face-specific Performance

Finally, we tested age differences in face-specific performance after accounting for general cognitive functioning. In order to stringently test age-associated differences in specific factors we used nested factor representations following recommendations by Schmiedek and Li (2004) and Hildebrandt et al. (2011) for overcoming problems associated with age mediation models. In the nested factor model (Model 5; Fig. 7, not displaying the age variable) FP and FM indicators are directly related with the general cognition factor. The fit of Model 5, including age and squared age as predictor for all factors was reasonable: $\chi2$ (182) = 447.462, CFI = .922, RMSEA = .072, SRMR = .054. Factor loadings ranged between .100 and .779 (see Table 4). Residual covariances between Gf1 and Gf2, WM1 and WM2, and OP1 and OP2 were .67, .62 and .26, respectively.

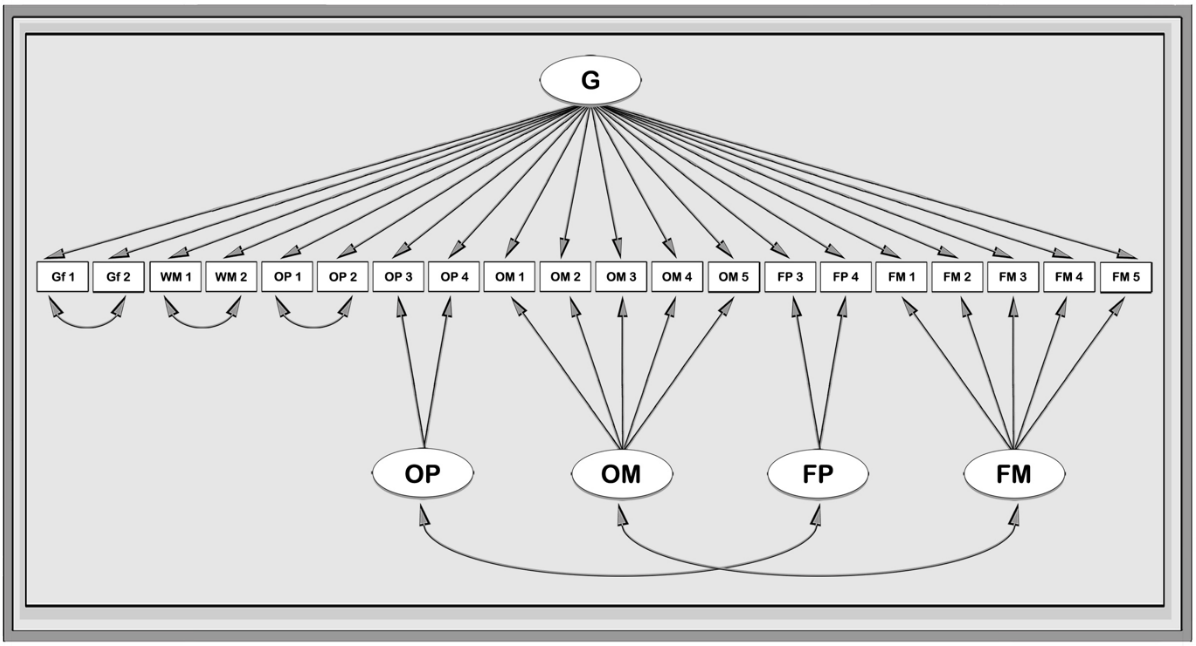

Figure 7. Schematic representation of the nested model of Face Cognition and General Cognitive Functioning. Face Perception (FP); Face Memory (FM); General Cognitive Functioning (G); Object Perception (OP); Object Memory (OM). By regressing these factors onto age, we tested age related performance differences in OP, OM, FP and FM controlling for variance due to general cognitive functioning.

Table 4. Factor loadings in the Nested Model of Face Cognition and General Cognitive Functioning

	Gf1	Gf2	WM1	WM2	OP1	OP2	OP3	OP4	OM1	OM2	OM3	OM4	OM5	FP3	FP4	FM1	FM2	FM3	FM4	FM5
G	.501	.598	.542	.638	.623	.779	.547	.504	.475	.581	.585	.586	.602	.716	.774	.495	.490	.463	.493	.703
OP	-	-	-	-	-	-	.678	.734	-	-	-	-	-	-	-	-	-	-	-	-
OM	-	-	-	-	-	-	-	-	.605	.586	.479	.450	.159	-	-	-	-	-	-	-
FP	-	-	-	-	-	-	-	-	-	-	-	-	-	.593	.487	-	-	-	-	-
FM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.555	.612	.581	.558	.100

Note. G - General Cognitive Functioning; WM – Working Memory; OP - Object Perception; OM - Object Memory; FP – Face Perception; FM – Face Memory

All factors in Model 5 (Fig. 7) were regressed onto the measured age and squared age variable to test quadratic age effects. Age was centered before computing squared age and running the analyses. Regression weights represent linear and quadratic age differences on the level of latent factors. The age-effect on G (β = .520; $p < .01$) reached statistical significance, but there was no quadratic effect of age on G. After accounting for G, there were no significant linear age effects on FP and FM, but a significant quadratic age effect on FP (β = .246; $p < .01$), indicating an accelerated increase of specific FP abilities in later adolescence after controlling for G.

Discussion

Previous studies on the specificity of face cognition abilities in childhood and adolescence arrived at inconsistent conclusions whether face cognition develops as a part of general cognitive functioning and differentiates later, or whether it is specific already during early periods of life (Crookes & McKone, 2009; Want et al., 2003; Weigelt et al., 2013). As discussed above, possible reasons for these inconsistencies may be disagreements in the choice of stimulus material, conclusions based on performance in (different) single tasks instead of latent variable and multivariate modelling of abilities, assembling arbitrary age groups, and disregarding individual differences within age cohorts.

The present study complements the (few) available psychometric studies of face cognition abilities in adulthood, which demonstrated that after the age of 18 years only half of the variance in face cognition can be explained by general cognitive functioning. These studies suggest substantial specificity of face cognition in adulthood (Hildebrandt et al., 2011; Wilhelm et al., 2010). By applying multiple tasks for the measurement of face- and general cognition, using face stimuli of various age groups, testing a large sample of children and adolescents aged between 6 and 20 years, and focusing on individual differences within each age cohort at the level of latent variables, we tested two hypotheses. First, following previous work of

Hildebrandt et al. (2011) and Wilhelm et al. (2010) assuming that face cognition is a specific ability facet of social intelligence, we adhered to the *theory of face-specific development* and expected no differentiation between face cognition abilities and general cognitive abilities from early school age to young adulthood. Face cognition abilities should be specific from earliest periods of life. Second, we expected that performance in face cognition abilities becomes adult-like only late (near young adulthood) and that performance improvements cannot be fully explained by general cognitive abilities.

Our results overall suggest that more than about 60% of the variance in face cognition abilities can be explained by general cognitive functioning in childhood and adolescence. However, the picture is complex on how the association between face cognition abilities and general cognitive functioning on the one hand and object cognition at the other hand differs across age. We observed a strong association between both face perception and memory abilities with general cognitive functioning that increased across age from about .40 (at the age of 8 years) to .80 (around the age of 20 years). This is evidence for slight dedifferentiation and conjoint maturation. Face perception and memory remain partly specific, but their association with general cognition increased across childhood and adolescence. For face perception as compared with object perception and face memory as compared with object memory there is an opposite tendency regarding their association trajectories across age. Face perception and face memory continuously differentiate from their object cognition counterparts. The associations decreased from .60 to around .20 between 8 and 20 years of age. Age-related differences in face cognition performance are not face-specific, but can be explained through the age-related linear increase of general cognitive functioning. There was, however, a quadratic age effect on face perception after G was controlled for, indicating a boost in face perception abilities later in adolescents going beyond maturation of general cognitive functioning. We will now discuss the findings summarized above in terms of developmental theories of face processing.

Association between Face Cognition and General Cognitive Functioning across Childhood and Adolescence

The finding that there is a substantial association between face cognition abilities and general cognitive functioning already in early periods of life that further increases till the age of about 14 years is partly consistent with the *theory of general cognitive development,* or *early maturity* view. As outlined in the introduction, this theory proposes that face cognition abilities do not follow a specific developmental trajectory but holds that maturation of face cognition can be explained by the development of other cognitive abilities (for reviews, Crookes & McKone, 2009; Want, et al., 2003; Weigelt, et al., 2013). Especially, supporters of the *theory of general cognitive development* point out the crucial influence of general cognitive functioning, because following instructions and focussing attention, working memory, and reasoning are helpful for mastering face cognition tasks as well. Thus, children with better developed general cognitive functioning demonstrate more adult-like levels of face cognition abilities (Betts, Mckay, Maruff, & Anderson, 2013; Lundy, Jackson, & Haaf, 2001). However, the present research demonstrates associations of face cognition with general cognition to become though increased with age, but they do not perfectly dedifferentiate, suggesting partial specificity of qualitative face cognition development during childhood and adolescence. Thus, we can conclude that face cognition abilities conjointly mature together with cognitive abilities (supporting the *theory of general cognitive development*). However, specific interests and investments in social context that children and adolescents make, would explain that face cognition is and remains a partly independent ability with respect to general cognitive functioning.

Association between Face Cognition and Object Cognition across Childhood and Adolescence

In contrast to the slight dedifferentiation of face cognition and general cognitive functioning, face perception and face memory show a tendency to increasingly differentiate from their object cognition counterparts from 8 to 20 years old. In addition, these abilities are already distinct at age six. These findings are consistent with many reports confirming the distinction on functional and neuroanatomical levels depending on the type of stimulus material in the same tasks (faces vs non-faces; for review see Maurer, Le Grand, & Mondloch, 2002, Rossion, 2013, Tanaka & Gordon, 2011). Therefore, face cognition is specific already in early school age and, hence, adult-like. Importantly, however, face specificity as compared with object perception and memory is shown here after controlling for general cognitive functioning. Thus, we may conclude that face perception and memory are distinct from perception and memory for non-face objects, but these abilities are highly related with the maturation of general cognitive functioning.

These findings combine the two conflicting views in research on the specificity of face cognition abilities in early periods of life (the *theory of general cognitive development* vs. the *theory of face-specific development*) and completes an attempt of Weigelt and colleagues (2013) to integrate these positions. Within the work of Weigelt and colleagues (2013) conclusions about the specificity of face cognition abilities were derived on the basis of performance in the same tasks but using different stimulus material. General cognitive development of participants was however not controlled for. Thus, the question arose, whether face cognition abilities are content-specific already in early childhood. As discussed in the introduction, content-specificity was observed only for face memory, but not for face perception. Weigelt et al. (2013) concluded that the *theory of face-specific development* holds for face memory, and the *theory of general cognitive development* holds for face perception. The present work we went a step further. By using a multiple measurements approach, we investigated age and individual differences in the covariance structure and in face cognition performance as compared not only with object cognition (object perception and object memory) but also with general cognitive functioning. Generally, face cognition abilities are adult-like in early school age. Individual differences in face cognition abilities in childhood and adolescence are highly, but not perfectly related with individual differences in general cognitive functioning. This conclusion is consistent with *the theory of general cognitive development.* We provided psychometric evidence for faces to be specific stimuli, transmitting relevant information about social life. This specific meaning of facial information makes face cognition abilities to be a partly independent performance construct, supporting *the theory of face-specific development.*

No Specific Age-Differences in Face Cognition Performance

Our results suggested that despite significant age-related increases in general cognitive functioning, there is no such increase in face perception performance and face memory after accounting for performance differences in general cognitive functioning. Therefore, apparent age-related improvements in face cognition performance may not be face-specific but merely a consequence of age-related improvements in general cognitive functioning. Children, who were able to follow instructions and concentrate the attention, who were better in working memory, reasoning, have demonstrated higher performance in face cognition tasks. Our findings are consistent with the *theory of general cognitive development,* or *early maturity* view: Already early school age children may have developed adult-like abilities in face cognition; however, individual differences in performance are highly related with development of other cognitive abilities (for reviews, Crookes & McKone, 2009; Want, et al., 2003; Weigelt, et al., 2013).

Limitations and a Tentative Solution for the Theoretical Controversy

By addressing the structure of face perception and object perception we first observed a perfect correlation between these factors. This was due to performance differences in the composite tasks for faces versus. Arguably, the composite task is the most frequently used procedure for measuring holistic face processing, that is, binding facial features into a gestalt (Hole, 1994; Young, et al., 1987). However, there is strong controversy about the most appropriate design to be applied in this task (Rossion, 2013 vs Richler & Gauthier, 2014). In the classic design, the top and bottom halves of different faces are combined into a new face, which tends to perceptually merge into a new "whole" face if the two halves are aligned with each other. Participants decide whether the top (or bottom) halves of two composite faces are the same or different. When the face halves of the composite faces are aligned it is more difficult to render the identity decision as compared with a non-aligned condition. This performance difference between aligned and nonaligned stimulus presentations is termed the composite face effect.

In comparison with the classic design of the composite task, in the modified, or so-called "complete design", both face halves varied (what is not done in the classic design). Therefore, in the complete design, there are congruent and incongruent trials where all face halves are aligned but in congruent trials the upper and lower halves of the two successive stimuli are from the same face or both are from different faces whereas in incongruent trials one of the face halves is composed from the same faces and the other from different faces, causing a perceptual conflict. Thus, the holistic face perception strategy is operationalized as a congruency effect – performance is more accurate in congruent trials.

Proponents of the "complete design" of the composite task criticized the classical design because it leads to response conflict. However, the complete design has also been criticized by researchers supporting more conservative measures of holistic face processing. Thus, it is contested whether the complete design measures a specific holistic face perception strategy or response conflict (Rossion, 2013). Following this reasoning, the complete design has been contraindicated to be used in studies with children, because the perceptual conflict may lead to high task difficulty and requires highly focussed attention (Rossion, 2013).

Our study is the first that used the modified version of the composite task and applied it to children and adolescence. However, the structure of face perception and object perception revealed a perfect correlation between Composite face task and Composite house task performance, indicating that this task does not specifically measure aspects of face perception. Therefore, the Composite tasks were not included in the target model of face cognition and general cognitive functioning in our study. Our results support the position, that the modified design of the composite task may not measure a specific holistic face processing ability. Thus, studies that use the composite paradigm should be interpreted differently as compared with other tasks measuring face perception.

Conclusion

In the present study of individual differences we addressed the theoretical controversy, discussing whether face cognition abilities are domain-specific already in earlier periods of life or whether they differentiate across childhood and adolescence. By applying an innovative measurement approach, using multiple tasks for measuring face, object, and general cognition, using face stimuli of various age groups, and testing a large sample aged between 6 to 20 years, we estimated age and individual differences in the covariance structure of face cognition abilities and general cognitive functioning as well as face cognition performance after accounting for general cognition. Our findings integrate the two conflicting views on the specificity of face cognition abilities in early life (the *theory of general cognitive development* vs. the *theory of face-specific development*). Overall we have shown that already six-years old children nay reach adult-like face cognition abilities. The level of the maturation of these abilities is highly related with general cognitive functioning. However, it is important to note, that faces are partly specific social stimuli and the maturation of face cognition abilities are also determined by the harmonious socialization of the child.

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Appendix

Table A1.

Number of Participants per Age Group and Gender

Age group	N_{total}	N_{boys}	N_{girls}
6-7	23	8	15
8	24	11	13
9	23	8	15
10	34	26	8
11	43	21	22
12	23	13	10
13	22	5	17
14	29	13	16
15	21	12	9
16	26	18	8
17	31	15	16
18-21	29	11	18
Total	338	162	166

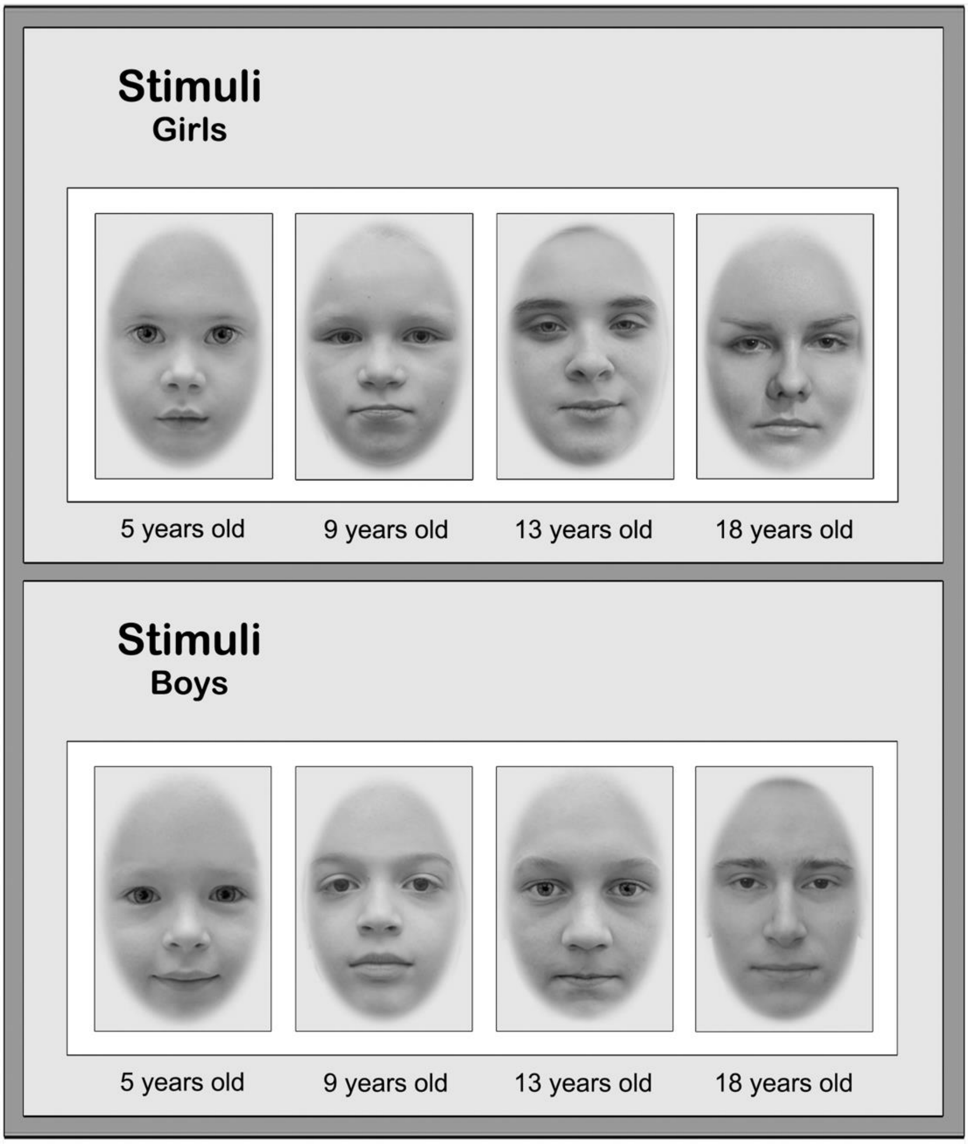

Figure A1. Examples for the face stimuli.

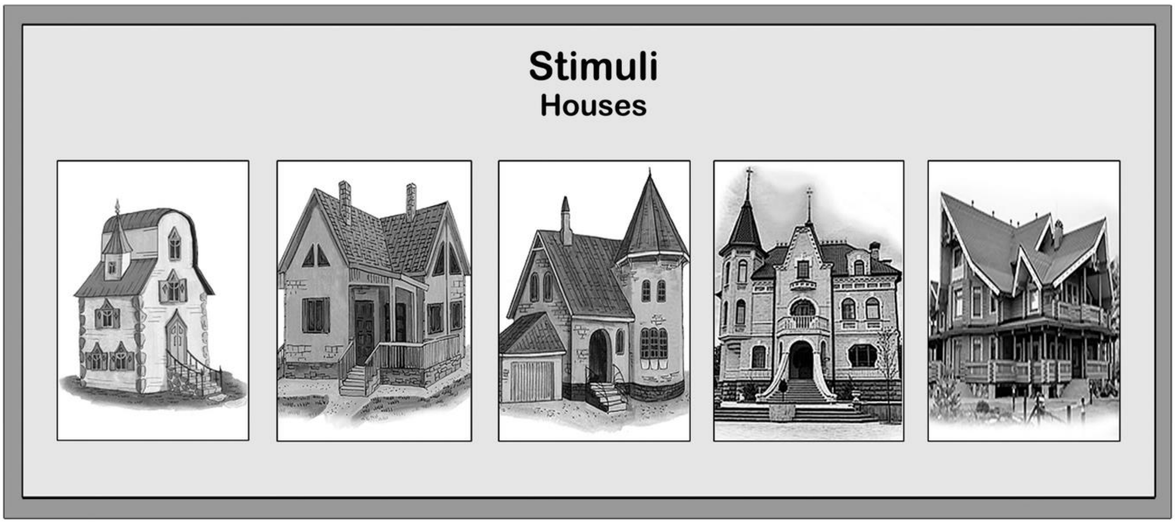

Figure A2. Examples for the houses stimuli.

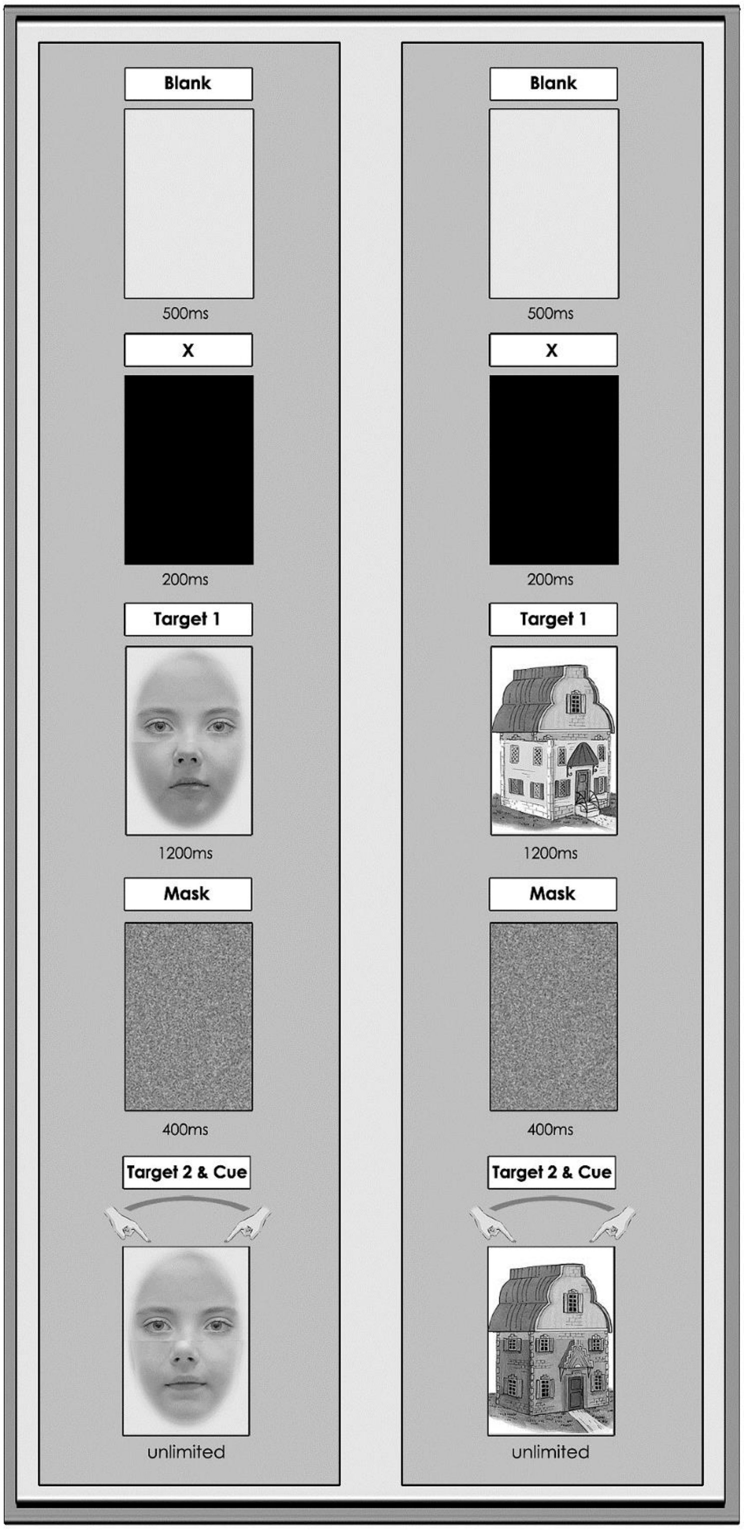

Figure A3. Example of a trial sequence in Composite tasks.

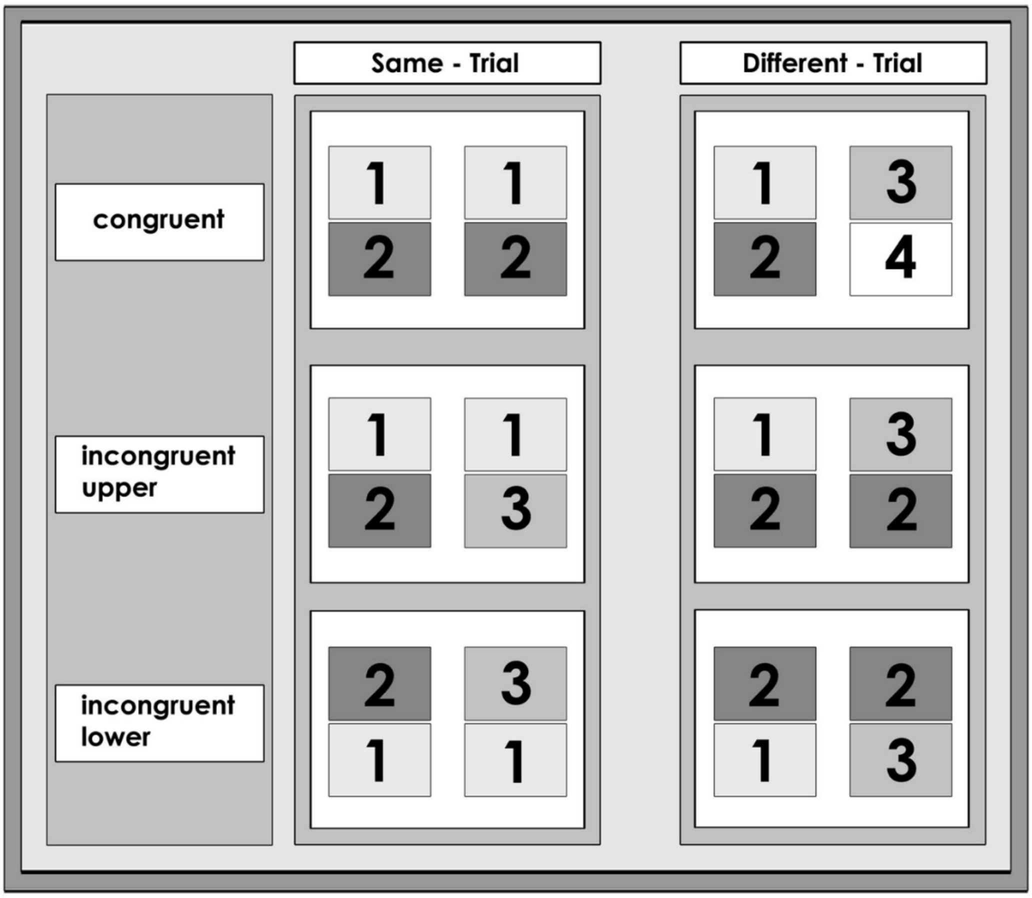

Figure A4. Overview of the Composite tasks conditions applied in the present study.

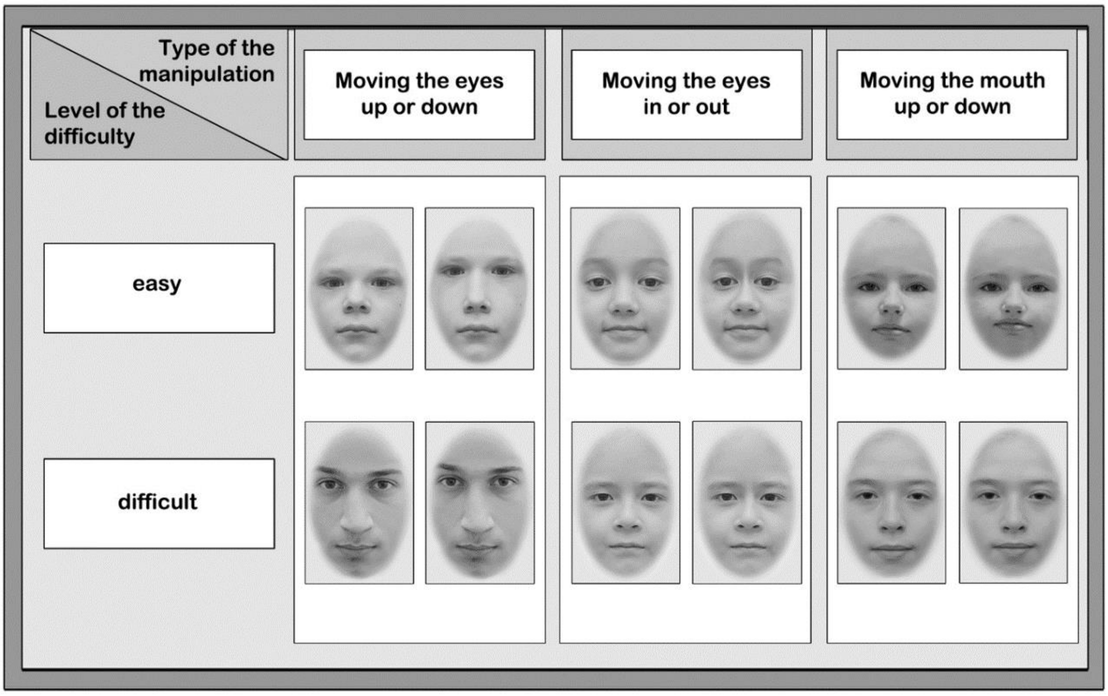

Figure A5. Overview of the levels of difficulty applied in the task Simultaneous matching of spatially manipulated faces with upright and inverted conditions (inverted not shown).

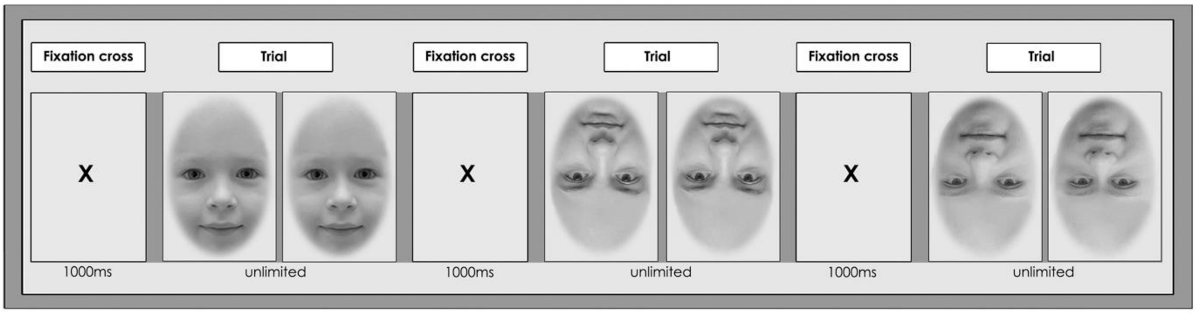

Figure A6. Example of a trial sequence in the task Simultaneous matching of spatially manipulated faces with upright and inverted conditions

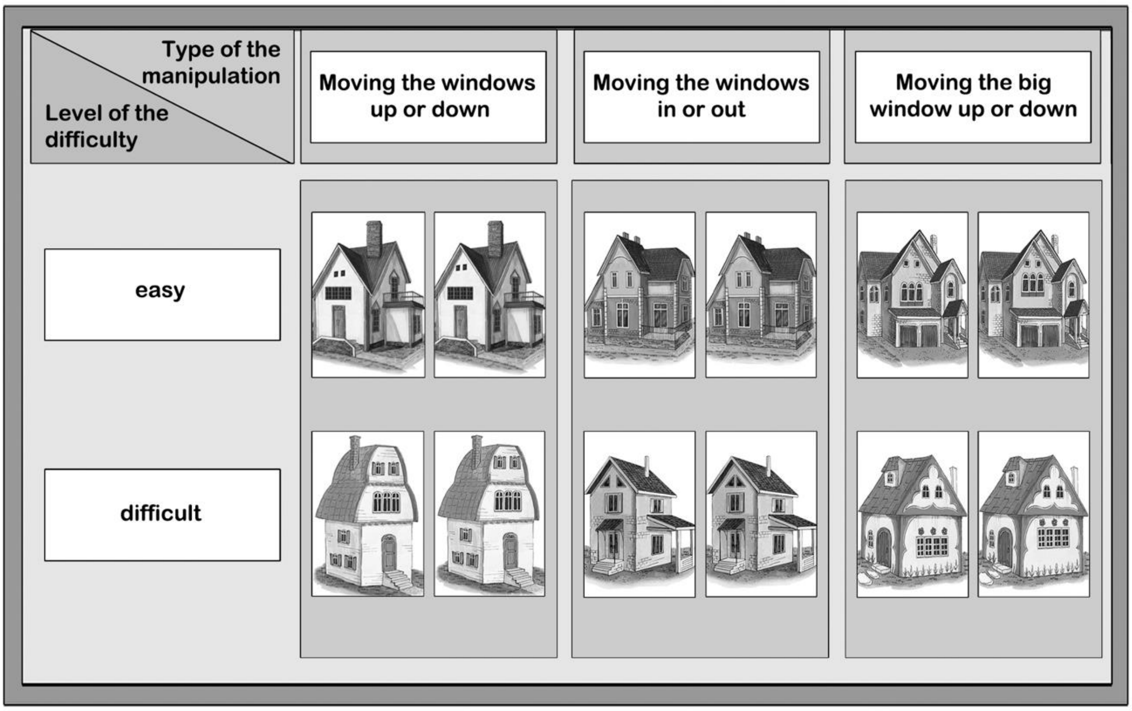

Figure A7. Overview of the levels of difficulty applied in the task Simultaneous matching of spatially manipulated houses with upright and inverted conditions (inverted not shown).

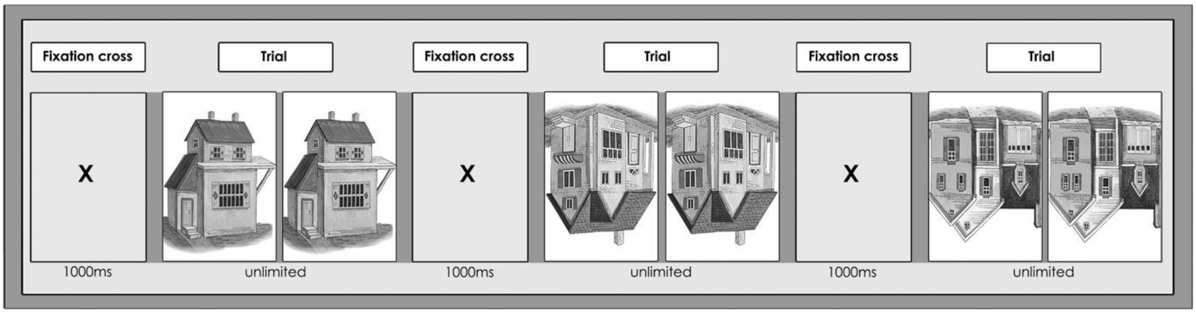

Figure A8. Example of a trial sequence in the task Simultaneous matching of spatially manipulated houses with upright and inverted conditions

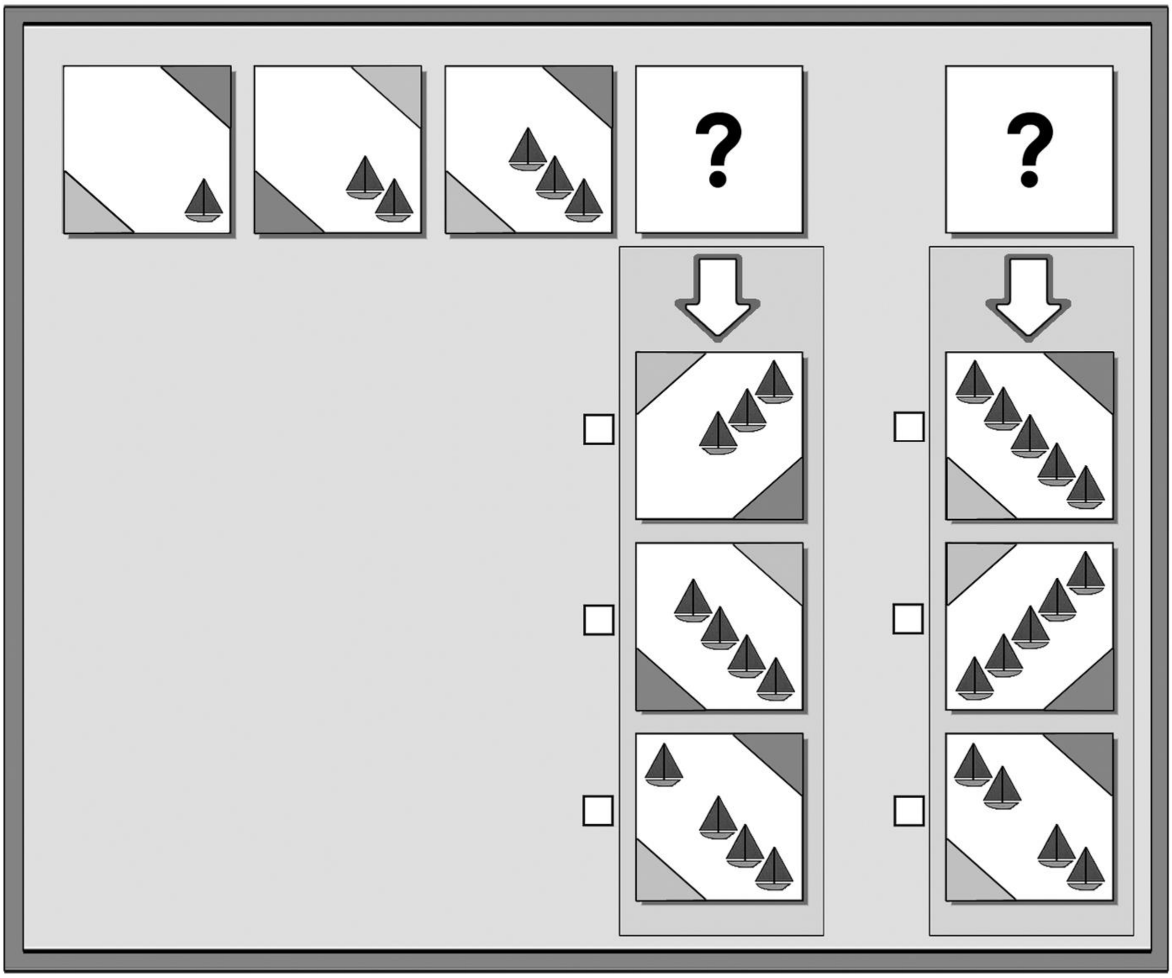

Figure A9. Example of an item taken from the reasoning task; BEFKI figural.

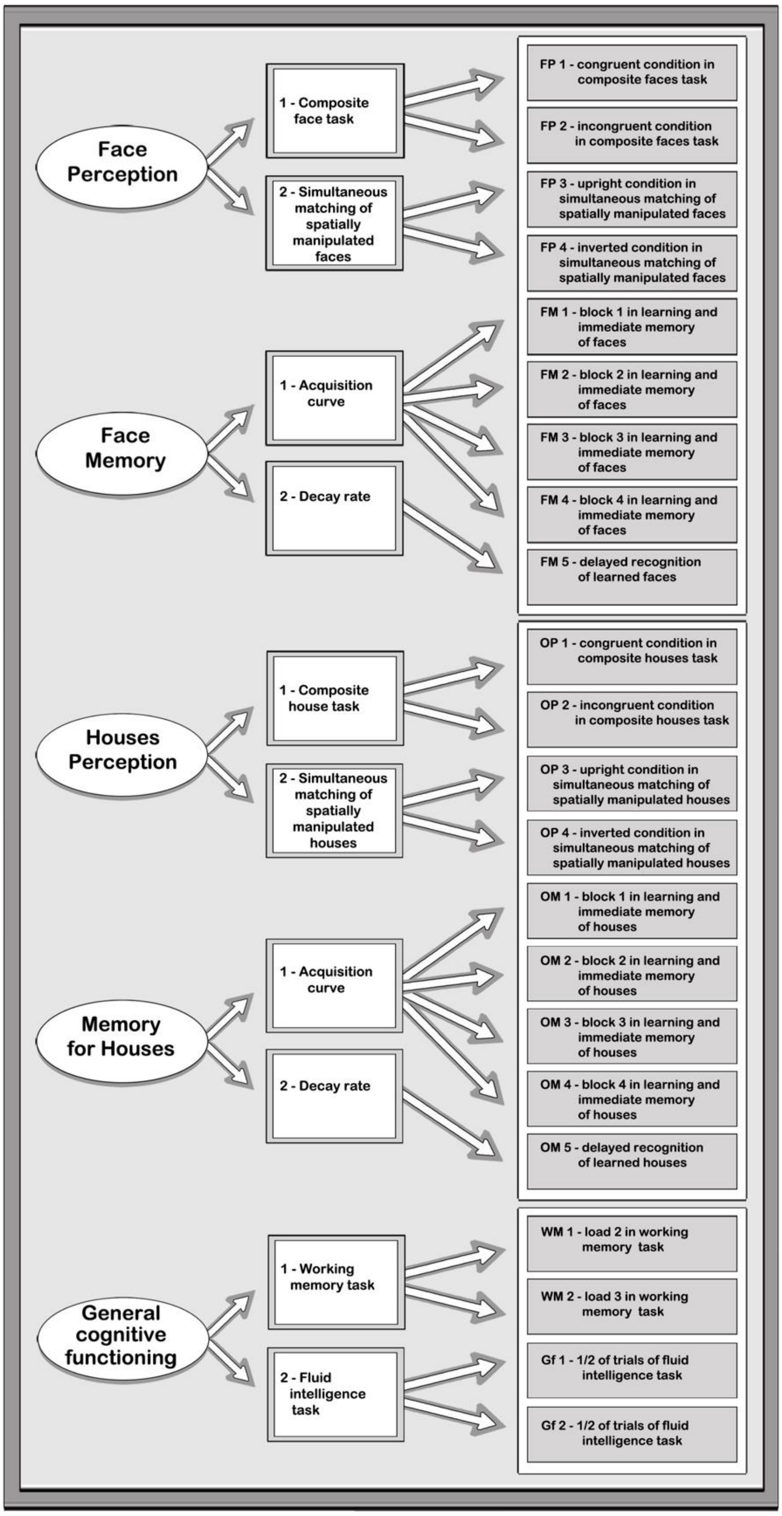
Face Perception
1 - Composite face task
2 - Simultaneous matching of spatially manipulated faces
FP 1 - congruent condition in composite faces task
FP 2 - incongruent condition in composite faces task
FP 3 - upright condition in simultaneous matching of spatially manipulated faces
FP 4 - inverted condition in simultaneous matching of spatially manipulated faces
Face Memory
1 - Acquisition curve
2 - Decay rate
FM 1 - block 1 in learning and immediate memory of faces
FM 2 - block 2 in learning and immediate memory of faces
FM 3 - block 3 in learning and immediate memory of faces
FM 4 - block 4 in learning and immediate memory of faces
FM 5 - delayed recognition of learned faces
Houses Perception
1 - Composite house task
2 - Simultaneous matching of spatially manipulated houses
OP 1 - congruent condition in composite houses task
OP 2 - incongruent condition in composite houses task
OP 3 - upright condition in simultaneous matching of spatially manipulated houses
OP 4 - inverted condition in simultaneous matching of spatially manipulated houses
Memory for Houses
1 - Acquisition curve
2 - Decay rate
OM 1 - block 1 in learning and immediate memory of houses
OM 2 - block 2 in learning and immediate memory of houses
OM 3 - block 3 in learning and immediate memory of houses
OM 4 - block 4 in learning and immediate memory of houses
OM 5 - delayed recognition of learned houses
General cognitive functioning
1 - Working memory task
2 - Fluid intelligence task
WM 1 - load 2 in working memory task
WM 2 - load 3 in working memory task
Gf 1 - 1/2 of trials of fluid intelligence task
Gf 2 - 1/2 of trials of fluid intelligence task

Figure A10. Schematic representation of the assignment of trials to indicators according to tasks.

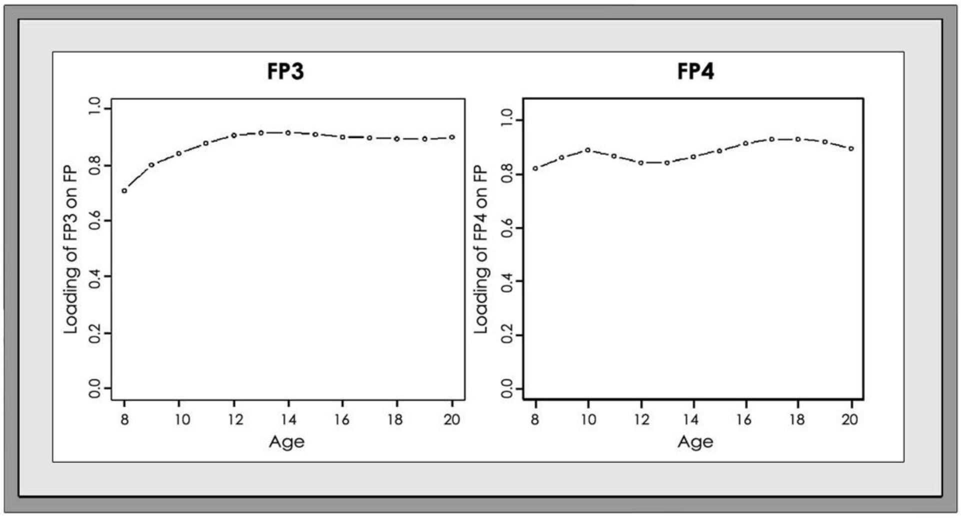

Figure A11A. LSEM-estimated age gradients of loadings for face perception across age.

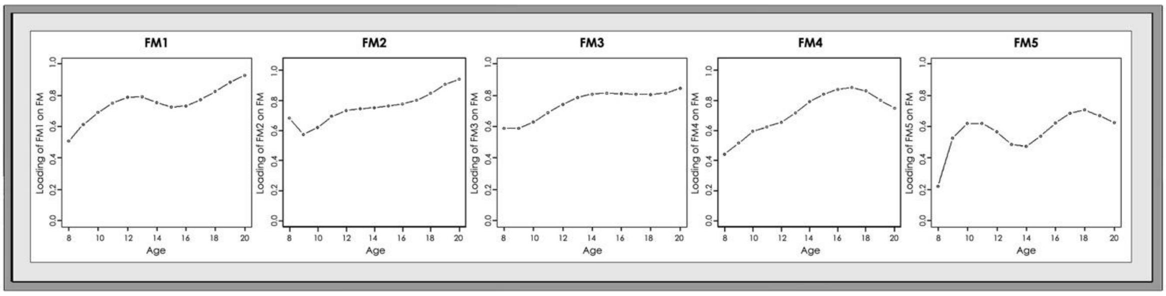

Figure A11B. LSEM-estimated age gradients of loadings for face memory across age.

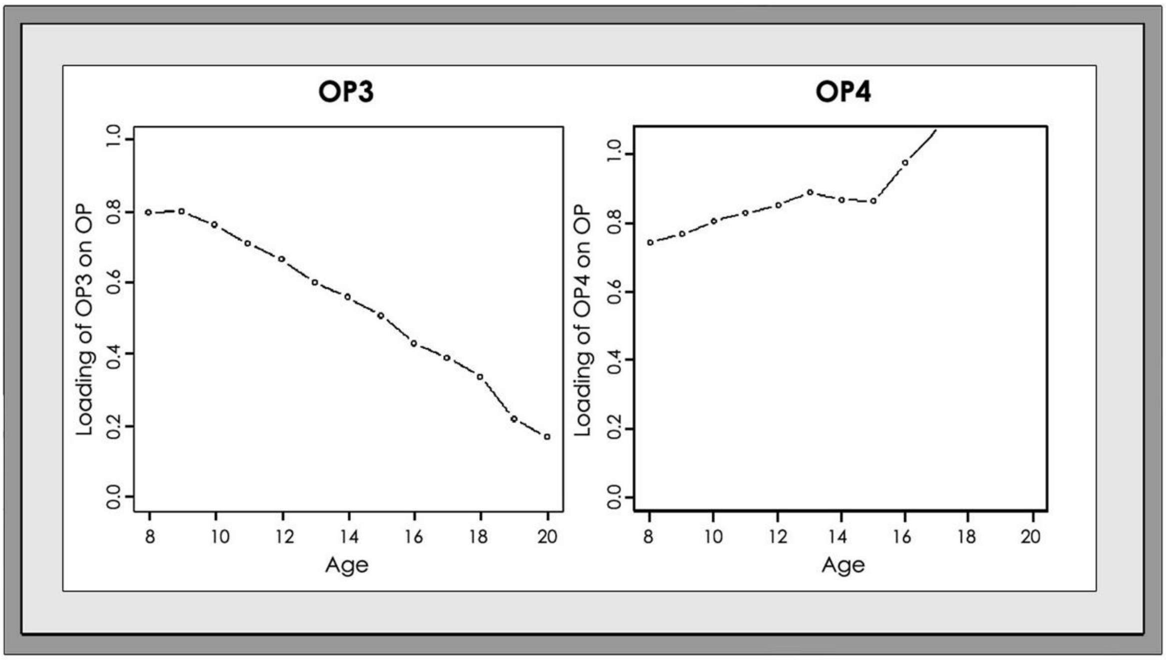

Figure A11C. LSEM-estimated age gradients of loadings for object perception across age.

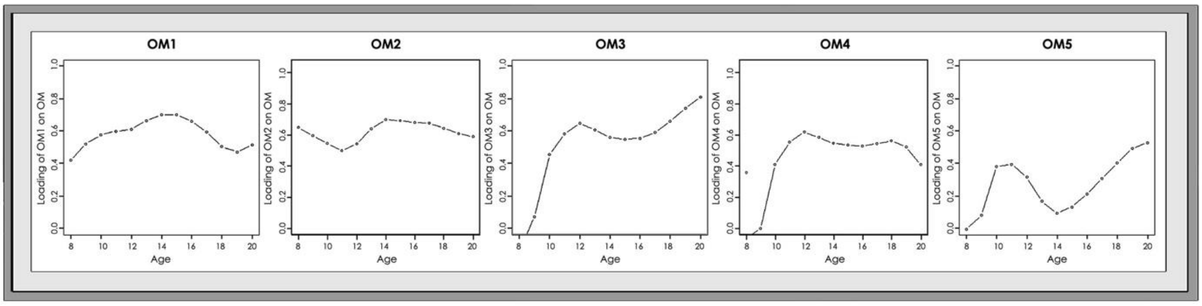

Figure A11D. LSEM-estimated age gradients of loadings for object memory across age.

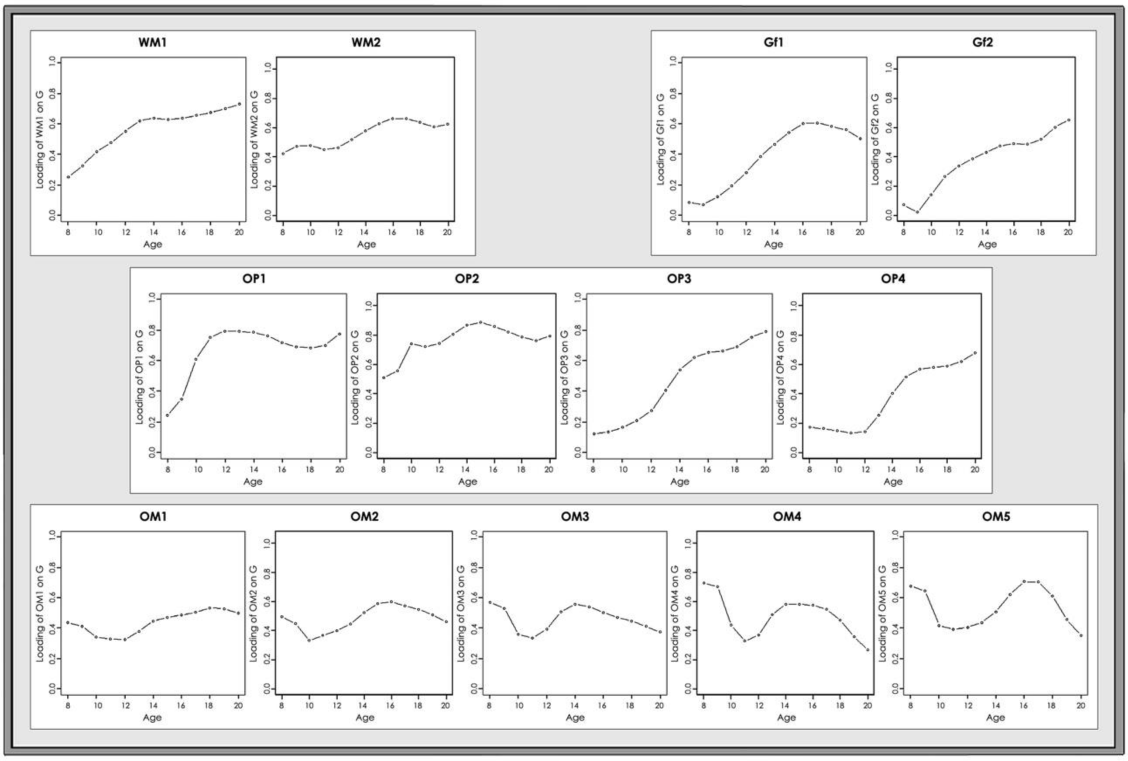

Figure A11E. LSEM-estimated age gradients of loadings for general cognitive functioning across age.

Eidesstattliche Erklärung

Erklärung:

Hiermit erkläre ich, die Dissertation selbstständig und nur unter Verwendung der angegebenen Hilfen und Hilfsmittel angefertigt zu haben.

Declaration:

I hereby declare that I completed the doctoral thesis independently based on the stated resources and aids.

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(Anastasia Petrakova)